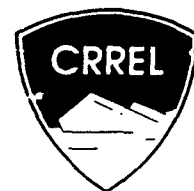


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Sorption of Trace-Level Organics by ABS, FEP, FRE and FRP Well Casings

Thomas A. Ranney and Louise V. Parker

June 1994

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Abstract

The first part of this report contains the results of a literature review on whether four polymeric materials [acrylonitrile butadiene styrene (ABS), fluorinated ethylene propylene (FEP), fiberglass-reinforced epoxy (FRE) and fiberglass-reinforced plastic (FRP)] should be used in well casings when monitoring groundwater. The second part of this report contains the results of a laboratory study that compares sorption of low (mg/L) levels of dissolved organics by these four materials with sorption by two commonly used polymeric well casing materials [polyvinyl chloride (PVC) and polytetrafluoroethylene (PTFE)]. During the six-week laboratory study, ABS sorbed analytes much more rapidly and to a greater extent than the other materials, and PVC and FRE sorbed analytes the most slowly and to the least extent of the materials tested. As the study progressed there were an increasing number of unidentified peaks in the HPLC chromatograms of some of the samples. By the end of the study (1000 hours), there were 11 additional peaks in the ABS samples, 5 in the FRP samples and 1 in the FRE samples. Analysis by purge-and-trap GC/MS of the 1000-hour samples and 500-hour samples from a leaching study revealed the identity of some of these peaks.

For conversion of SI metric units to U.S./British customary units of measurement consult *Standard Practice for Use of the International System of Units (SI)*, ASTM Standard E380-89a, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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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 Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). Funding for this work was provided by the U.S. Army Environmental Center (USAEC, formerly USATHAMA), Aberdeen Proving Ground, Maryland, Martin H. Stutz, Project Monitor.

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Sorption of Trace-Level Organics by ABS, FEP, FRE and FRP Well Casings

THOMAS A. RANNEY AND LOUISE V. PARKER

INTRODUCTION

Ideally any material 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 not affect analyte concentrations in samples by leaching or sorbing organics or metals, and should resist degradation by the environment. Recent guidance by the U.S. Environmental Protection Agency (U.S. EPA 1992) acknowledges that none of the most commonly used well casing materials in groundwater monitoring [polytetrafluoroethylene (PTFE), polyvinylchloride (PVC) or stainless steel (SS)] can be used for all monitoring applications. PVC and especially PTFE are not strong enough to be used in the deepest of wells (Table 1), and PVC and SS can both be degraded by certain environments. PVC is degraded by several neat solvents, including low-molecular-weight ketones, aldehydes, amines, and chlorinated alkanes and alkenes (Barcelona et al. 1984). PVC can also be degraded by high concentrations (near solubility) of

some of these solvents. Stainless steel will be corroded if any of the following conditions exist: low pH, high dissolved oxygen and carbon dioxide levels, or high levels of hydrogen sulfide, dissolved solids or chlorides (Driscoll 1986, Aller et al. 1989). Previous studies by this laboratory (Hewitt 1989, 1992, Parker et al. 1990) and others (Reynolds and Gillham 1986, Gillham and O'Hannesin 1990, Reynolds et al. 1990) have shown that none of these materials are chemically inert with respect to sorption and leaching of analytes of interest. Specifically, PVC and PTFE sorbed organics, and PVC and SS sorbed and leached metals.

There are other materials that are being (or have been) used for either well casings or sampling pipe that should be evaluated. Four alternative materials are acrylonitrile butadiene styrene (ABS), fluorinated ethylene propylene (FEP), fiberglass-reinforced epoxy (FRE) and fiberglass-reinforced plastic (FRP).

ABS is a thermoplastic material like PVC and is a terpolymer of acrylonitrile, butadiene and styrene. A wide range in properties can be achieved by varying the ratio of the monomers and by using other monomers and 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). FRE is constructed of 75% high-silica glass and 25% high-purity, closed-molecular epoxy. According to Cowgill (1988) it is manufactured from bisphenol-A-type epoxy resins cured with methyl tetrahydrophthalic anhydride. According to the manufacturer's literature, the FRP used in this study was made with polyester resin approved by the Federal Food and Drug Administration and consisted of 70% fiberglass and 30% resin by weight.

Table 1. Recommended maximum depths for using various well casings.

Material	Depth (ft)	Depth (m)
PTFE*	225-375	68.6-114
PVC*	1200-2000	366-610
ABS*	1200-2000	366-610
FRE*	—	—
SS*	unlimited	unlimited
FRP†	1400**–700††	427**–213††

* Data from Neilsen and Schalla (1991).

† Data supplied by manufacturer.

** For 4.5-in.-ID screen.

†† For 16-in.-ID screen.

Our first objective was to find what was known in the literature regarding the suitability of these materials for use in groundwater monitoring wells. Specifically we wanted to address whether these materials were strong enough to be used as casings in a well, could withstand chemical attack, and were relatively inert with respect to sorption and leaching of analytes of interest.

LITERATURE REVIEW

Physical strength

FRE is nearly as strong as stainless steel, while the strength of ABS is more like that of PVC pipe (Table 2). We were unable to find information equivalent to that given in Table 2 for FRP. However, according to the manufacturer, it can be used to approximately the same depths as PVC and ABS

Table 2. Strength of 2-inch nominal well casings. (From Nielsen and Schalla 1991.)

Material	Casing tensile strength (lb)	Collapse strength (psi)
PTFE	3,800	—
PVC	7,500	307
ABS	8,830	—
FRE	22,600	330
SS	37,760	896

casings (Table 2) and thus is presumably equally as strong. We also did not find any information on the strength of FEP. Again, we presume its strength would be similar to that of PTFE.

Thus, while all these materials can be used for well casings in at least some instances, further confirmation of the manufacturer's guidelines for maximum sampling depth is needed for FRP. If FEP is found to be a desirable alternative to PTFE, then strength data would also be needed for this product.

Resistance to chemical attack

Several of these polymers are degraded by corrosive reagents and neat organic solvents. FEP is like PTFE and other fluoropolymers in that it has excellent resistance to attack by corrosive reagents and dissolution by solvents. FRE is reported by its manufacturer to be impervious to gasoline, hydrocarbon products, and most solvents and additives. While the most recent version of the Cole-Parmer Catalog (Cole-Parmer Instrument Company 1992) does state that "epoxy" has good resistance to fuel

oils, gasoline, jet fuel and kerosene, it also claims that it is moderately affected by several ketones and is severely degraded by dichloroethane, dimethyl formamide, benzaldehyde and others. (See Appendix A for a more complete listing.) According to the same source (Cole-Parmer Instrument Company 1992), ABS is severely degraded by a number of organic chemicals, including several ketones, chlorinated alkanes and alkenes, and several hydrocarbons such as fuel oils, gasoline and kerosene. (See Appendix A for a more complete listing.) However, this source does not give any detail on the type of epoxy or ABS materials that were tested.

The manufacturer of the FRP casings claims that their product is resistant to corrosion but makes no claims about its resistance to solvents. Since the manufacturer did not specify which particular polyester was used in their product, we cannot discuss its chemical resistance except in generic terms. According to Sax and Lewis (1987), polyesters are resistant to corrosive chemicals and solvents. However, Fuchs (1989) listed at least one organic compound that was a good solvent for each of the polyesters he listed.

Thus, it appears that between ABS, FEP and FRE, FEP is the most resistant polymer to degradation, while ABS is the least resistant. Clearly further testing of the chemical resistance of ABS, FRE and FRP well casings is needed.

Leaching of metals and organics

Metals

We found only one laboratory study that dealt with the leaching of metals from one of these materials (FRE). This study (Cowgill 1988) looked for the leaching of 30 elements from a ground powder of FRE well casings. No elements leached after 72 hours, but after three weeks, mg/L levels of B and Cl and $\mu\text{g/L}$ levels of P, Mg and Zn were found. These elements were either below the EPA's drinking water standards or were not regulated.

We did not find any other studies on any of the other materials. Presumably because of its composition, FEP would behave similarly to PTFE. Hewitt (1989, 1992) found that PTFE leached substantially less metals than PVC and (especially) SS materials.

While it appears that relatively low levels of some inorganics are leached from FRE, further studies on the leaching of metals from ABS, FRP and FEP are needed.

Organics

Cowgill (1988) also tested intact FRE well casings and a ground powder of these casings for

leaching of any organic substance involved in its manufacture and any of the U.S. EPA priority pollutants. No organics were detected following 72 hours of leaching of the powder, but low levels of diethylphthalate and bisphenol A were leached from the powdered well casings after three weeks. Cowgill noted that bisphenol A is a component of manufacture; diethylphthalate is a commonly used plasticizer. However, neither of these compounds was leached from the intact well casing pieces after three weeks and thus should not be of concern when monitoring for organics.

We were unable to find any studies on the leaching of organics from the other materials or any additional studies on FRE. ABS is a thermoplastic material and is fabricated using types of ingredients (heat stabilizers, fillers, pigments, lubricants and component monomers) similar to those used in manufacturing PVC. Presumably the same types of ingredients could leach from this product as have been seen with PVC. However, leaching of organics from PVC has been found to be considerably less problematic for rigid PVC, such as pipes and casings, than for flexible tubing (Miller 1982, Curran and Tomson 1983). [This is mainly because rigid PVC products contain almost no plasticizers (<0.01%) (Barcelona et al. 1984).] Presumably FEP would behave similarly to PTFE. Several studies (Curran and Tomson 1983, Barcelona et al. 1985) have shown that PTFE leaches relatively few organic impurities.

While it appears that leaching of organics from intact FRE should not present a problem when monitoring groundwater, further studies are needed on this issue for ABS, FRP and FEP.

Sorption of metals and organics

Surfaces that initially possess higher free energies have the most to gain in terms of decreasing the free energy of their surface by adsorption. Silica glass, metals and metal oxides are some examples of high-energy surfaces, while solid organic compounds, including most polymers, have low-energy surfaces (Hiemenz 1986). Thus, we might expect the polymers used in this study to be less adsorptive than stainless steel casings. We would expect that this would be true for inorganics, where adsorption is involved, but not for organics, where absorption within the polymer matrix is believed to occur (Reynolds and Gillham 1986, Gillham and O'Hannesin 1990, Parker et al. 1990).

Metals

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) also found that PTFE and rigid PVC did not sorb the two anions that he tested, As and Cr. However, sorption of cations by these polymers does appear to occur (Masse et al. 1981, Parker et al. 1990, Hewitt 1992). We found only one laboratory study (Raber et al. 1983) that actually tested the sorption of metals by any of the materials (FEP) used in this study. This study tested several polymers for the sorption of three radionuclides (SeO_3^{2-} , Sr^{2+} and Cs^+) and found that FEP was among the least sorptive materials. Again, previous performance by PTFE may be an indication of how FEP will perform, and Hewitt (Hewitt 1989, 1992, Parker et al. 1990) found relatively little sorption of several cations (Pb, Cd, Cu, Fe) by PTFE when compared with PVC and especially SS casings. Further research on the sorption of metals is needed for all these materials.

Organics

We did find two studies that addressed sorption of low concentrations of organics in aqueous solutions by FEP, FRE and ABS. Gillham and O'Hannesin (1990) conducted a study that compared sorption of ppb levels of six (mono) aromatic hydrocarbons by FRE, SS, PTFE, polyethylene (PE) and rigid and flexible PVC (RPVC and FPVC, respectively). They ranked the sorptiveness of the materials as (going from most sorptive to least): FPVC > PE > PTFE > FRE > RPVC > SS.

Jones and Milier (1988) also compared sorption of a number of organics from aqueous solution by SS, (rigid) PVC, ABS, FEP, PTFE and polyvinylidene fluoride (PVDF). However, it is not clear what caused the losses they observed, since no biocide was added to prevent losses due to biological activity and there did not appear to be any controls that losses could be compared with. Because they were unable to recover most of the constituents that were lost to "sorption" by the casings, it appears that at least some of these losses may be attributable to other causes, such as biodegradation, sorption by the container walls or the cap, or volatilization.

With respect to sorption of organics, further studies need to be conducted using ABS, FRP and FEP since there has been little study of these materials. While FRE appears to sorb organics more slowly than PTFE, further studies are needed on a wider spectrum of organics.

Conclusions from the literature review

Although these materials may be strong enough to be used as well casings, there has been relatively

little study of whether they can withstand chemical attack and whether they sorb or leach analytes of interest. We have initiated several research studies to address these deficiencies.

SORPTION OF ORGANICS

This study examines sorption of low (mg/L) levels of 11 organics by these four materials, PVC and PTFE.

Materials and methods

Sorption of organics

Six types of 5-cm- (2-in.-) diameter well casing or pipe were used in this study: PVC, PTFE, FEP, ABS, FRE and FRP. For PVC, PTFE, FRP and FRE, 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." When we tried to purchase the ABS well casing, we found that these manufacturers had apparently gone out of business. Thus, we purchased waste and vent pipe. Because wall thickness varied between these materials, sections of different widths were cut so that the final surface areas would be constant. Special care was taken to eliminate contamination from grease or oil during the cutting process. All the pieces were placed in solutions of detergent and deionized water and sonicated for 20 minutes, then rinsed several times with deionized water to remove the detergent, sonicated for 20 minutes in fresh deionized water, rinsed, drained and left to air dry.

Two pieces of one of these materials were placed in individual 40-mL borosilicate glass vials. The vials were then filled with aqueous test solution so that there was no headspace and then capped with Teflon-lined plastic caps. Vials with test solution but no material served as controls. These controls allowed us to correct for any effects that might be due to the vials or caps. The approximate ratio of material surface area to solution volume was 0.79 cm²/mL. Separate vials were used for each sampling period so that the test solution could be discarded after sampling. For each material and time, there were three replicates.

The experiment investigated the sorption of cis-1,2-dichloroethylene (CDCE), trans-1,2-dichloroethylene (TDCE), benzene (BENZ), *m*-nitrotoluene (MNT), trichloroethylene (TCE), chlorobenzene (CLB), *o*-dichlorobenzene (ODCB), *o*-xylene (OXYL), *p*-dichlorobenzene (PDCB), *m*-xylene (MXYL) and tetrachloroethylene (perchloroethylene or PCE). The

test solutions were all prepared by adding each of the neat organics directly to well water taken from a deep water well (in Enfield, New Hampshire) in 2-L volumetric flasks. Because three solvents were less dense than water and floated, a small headspace of approximately 1 mL was left at the top of the volumetric flask so when the glass stopper was inserted there would be no solvent loss. Parafilm was used to seal the glass stopper to minimize vapor loss. Forty mg/L of HgCl₂ was added to the test solutions to prevent any biological activity. The initial concentrations of analytes varied from 1 to 2 mg/L, with the exception being BENZ, which had a concentration of approximately 0.5 mg/L. The solutions were stirred with a magnetic bar for approximately three days. Prior to starting the experiment, we checked the test solutions using a magnifying glass to make sure that there were no undissolved droplets of solvent remaining.

Sets of seven vials containing the six materials plus the controls were then filled in a random order. The samples were kept at room temperature and in the dark for 1 hour, 8 hours, 24 hours (1 day), 72 hours (3 days), 168 hours (1 week), 500 hours (3 weeks) and 1000 hours (6 weeks).

For analysis of each sample, a small aliquot of solution was transferred (using a glass Pasteur pipet) to an autosampler vial (1.8 mL), which was gently filled so there was no headspace and then capped. Teflon-backed silicone septa were used in the autosampler vials. Analytical determinations of the organic solute concentrations were by reversed-phase high-performance liquid chromatography (RP-HPLC). A modular system was employed that consisted of a Spectra Physics SP 8810 isocratic pump, a Spectra Physics SP 8490 variable-wavelength UV detector set at 210 nm, a Spectra Physics SP 8875 autosampler with a 100- μ L injection loop, and a Hewlett-Packard 3396 series II digital integrator. Separations were obtained on a 25-cm $\times$ 4.6 mm (5 μ m) LC-18 column (Supelco) eluted with 62/38 (v/v) methanol/water at 1.5 mL/min. The detector response was obtained from the digital integrator operating in the peak height mode. Retention times of the analytes ranged from 4.0 to 16.3 minutes.

Leaching of contaminants

When we compared the chromatograms of samples exposed to the casings with those for the control samples, we saw additional peaks in some of the samples. Thus, we decided to analyze the 1000-hour samples using purge-and-trap GC/MS to try to identify at least some of these peaks. For these analyses, EPA Method 8240 for volatile organics by GC/MS (U.S. EPA 1986) was used. The GC/MS

system consisted of a Tekmar LSC-2 liquid sample concentrator, a Hewlett Packard 5890 series II gas chromatograph, and a Hewlett Packard 5970 series mass selective detector. One sample for each type of material was analyzed, plus a control sample.

To confirm that the organics we had found in the test solutions resulted from leaching from the casing materials, we placed two pieces of the cleaned casing material (the same size as used previously) in 40-mL glass vials. These vials were then filled with the well water so that there was no headspace. The well water also contained 40 mg/L of HgCl_2 to prevent any biological activity. These samples were analyzed after approximately 500 hours of contact time, using purge-and-trap GC/MS (EPA method 8240). We tested only those materials that appeared to be leaching contaminants in the previous study (ABS, FRE and FRP) and a blank (water only); there were no replicates in this study.

Results and discussion

Sorption of organics

The analyte concentration for each sample (in

mg/L), the mean concentration for each material and time, and the standard deviation and relative standard deviation (%RSD) for each material and time are given in Appendix B. These data are summarized in Table 3, where the means of the normalized concentrations for the materials are given with time. (Mean normalized values were determined by dividing the mean concentration for a particular material and time by the mean concentration of the control samples for the same time.) For each material and time, the relative standard deviation was below 10% except for some of the later ABS samples. The relative standard deviations were high for some ABS samples when the concentrations approached the detection limit. The trends in sorption by the various materials can be seen in Figure 1.

For each analyte and time, a one-way analysis of variance test (ANOVA) was performed to determine if there were any significant differences between the various treatments (polymers and controls) (at the 95% confidence level). When a significant difference was found, a Duncan's Multiple Range test was performed to determine which ma-

Table 3. Means of normalized concentrations of analytes exposed to test materials. For each analyte, values with the same superscript are not significantly different from each other. Values with "1" were not significantly different from the controls.

Analyte Treatment	1 hr	8 hr	24 hr	72 hr	168 hr	500 hr	1000 hr
CDCE	PVC 0.98 ¹	0.98 ¹	0.97 ¹	0.99 ¹	0.97 ^{1,2}	0.94 ²	0.90 ²
	PTFE 0.99 ¹	0.95 ^{1,2}	0.94 ¹	0.93 ²	0.90 ³	0.85 ³	0.79 ³
	FEP 1.00 ¹	0.96 ^{1,2}	0.94 ¹	0.95 ^{1,2}	0.92 ³	0.88 ³	0.81 ³
	ABS 0.93 ¹	0.81 ³	0.74 ³	0.63 ⁴	0.51 ⁵	0.36 ⁵	0.26 ⁵
	FRE 0.99 ¹	0.96 ^{1,2}	0.94 ¹	0.93 ²	0.96 ²	0.95 ²	0.91 ²
	FRP 0.97 ¹	0.89 ^{2,3}	0.85 ²	0.81 ³	0.82 ⁴	0.78 ⁴	0.68 ⁴
TDCE	PVC 0.98 ¹	0.96 ¹	0.95 ^{1,2}	0.96 ¹	0.92 ²	0.89 ²	0.75 ³
	PTFE 0.97 ¹	0.91 ^{1,2}	0.86 ³	0.80 ⁵	0.72 ⁴	0.65 ⁴	0.54 ⁵
	FEP 0.97 ¹	0.92 ^{1,2}	0.87 ³	0.84 ³	0.77 ³	0.71 ³	0.57 ^{4,5}
	ABS 0.89 ²	0.75 ³	0.65 ⁵	0.51 ⁵	0.39 ⁵	0.28 ⁵	0.19 ⁶
	FRE 0.98 ¹	0.94 ¹	0.92 ³	0.90 ²	0.93 ²	0.96 ¹	0.88 ²
	FRP 0.94 ^{1,2}	0.84 ²	0.79 ⁴	0.73 ⁴	0.74 ^{3,4}	0.75 ³	0.60 ⁴
TCE	PVC 0.98 ^{1,2}	0.96 ^{1,2}	0.96 ^{1,2}	0.98 ¹	0.95 ²	0.93 ²	0.82 ³
	PTFE 0.96 ^{1,2}	0.89 ^{2,3}	0.83 ³	0.75 ³	0.64 ³	0.51 ⁴	0.39 ⁵
	FEP 0.96 ^{1,2}	0.89 ^{2,3}	0.83 ³	0.78 ³	0.68 ³	0.57 ³	0.44 ^{4,5}
	ABS 0.85 ²	0.62 ⁴	0.47 ⁴	0.32 ⁵	0.21 ⁴	0.13 ⁵	0.09 ⁶
	FRE 0.98 ^{1,2}	0.95 ^{1,2}	0.94 ²	0.91 ²	0.94 ²	0.95 ^{1,2}	0.88 ²
	FRP 0.94 ^{1,2}	0.85 ³	0.77 ³	0.69 ⁴	0.66 ³	0.60 ³	0.46 ⁴
PCE	PVC 0.98 ^{1,2}	0.95 ¹	0.94 ¹	0.95 ^{1,2}	0.93 ²	0.94 ²	0.77 ³
	PTFE 0.92 ^{1,2}	0.78 ²	0.65 ³	0.50 ⁴	0.36 ⁴	0.24 ⁵	0.15 ⁵
	FEP 0.90 ²	0.76 ²	0.63 ³	0.51 ⁴	0.40 ⁴	0.29 ⁴	0.19 ⁵
	ABS 0.78 ³	0.44 ³	0.24 ⁴	0.12 ⁵	0.07 ⁵	0.05 ⁶	0.04 ⁶
	FRE 0.98 ^{1,2}	0.95 ¹	0.94 ¹	0.92 ²	0.96 ^{1,2}	1.02 ¹	0.92 ²
	FRP 0.94 ^{1,2}	0.84 ²	0.76 ²	0.67 ³	0.63 ³	0.56 ³	0.36 ⁴
BENZ	PVC 0.99 ¹	0.98 ¹	0.99 ¹	1.00 ¹	0.99 ¹	0.98 ^{1,2}	0.95 ²
	PTFE 0.99 ¹	0.95 ¹	0.94 ^{1,2}	0.93 ^{2,3}	0.89 ²	0.84 ³	0.77 ³
	FEP 1.00 ¹	0.95 ¹	0.93 ^{1,2}	0.94 ^{1,2}	0.90 ²	0.86 ³	0.78 ³
	ABS 0.91 ²	0.77 ²	0.68 ³	0.55 ⁴	0.42 ³	0.27 ⁴	0.19 ⁴
	FRE 1.00 ¹	0.95 ¹	0.94 ^{1,2}	0.96 ^{1,2}	0.97 ¹	0.96 ²	0.93 ²
	FRP 0.98 ^{1,2}	0.92 ¹	0.90 ²	0.87 ³	0.88 ²	0.83 ³	0.74 ³
CLB	PVC 0.98 ¹	0.97 ^{1,2}	0.97 ¹	0.98 ^{1,2}	0.95 ²	0.93 ²	0.86 ²
	PTFE 0.97 ¹	0.92 ^{2,3}	0.89 ²	0.82 ³	0.75 ³	0.62 ⁴	0.50 ⁴
	FEP 0.98 ¹	0.92 ^{2,3}	0.88 ²	0.84 ³	0.77 ³	0.67 ³	0.55 ³
CLB	ABS 0.85 ²	0.53 ⁴	0.35 ⁴	0.20 ⁵	0.12 ⁵	0.07 ⁶	0.05 ⁶
	FRE 0.99 ¹	0.96 ^{1,2}	0.95 ¹	0.93 ¹	0.95 ²	0.95 ²	0.89 ²
	FRP 0.96 ¹	0.88 ³	0.81 ³	0.73 ⁴	0.69 ⁴	0.58 ⁵	0.42 ⁵
ODCB	PVC 0.98 ¹	0.96 ^{1,2}	0.96 ^{1,2}	0.96 ^{1,2}	0.94 ²	0.92 ²	0.86 ²
	PTFE 0.97 ¹	0.91 ^{2,3}	0.86 ³	0.78 ³	0.69 ³	0.54 ⁴	0.42 ⁴
	FEP 0.98 ¹	0.90 ^{2,3}	0.85 ³	0.78 ³	0.71 ³	0.58 ³	0.46 ³
	ABS 0.81 ²	0.41 ⁴	0.18 ⁵	0.08 ⁵	0.04 ⁵	0.02 ⁶	0.02 ⁶
	FRE 0.99 ¹	0.96 ^{1,2}	0.94 ²	0.92 ²	0.94 ²	0.93 ²	0.88 ²
	FRP 0.95 ¹	0.87 ³	0.78 ⁴	0.67 ⁴	0.60 ⁴	0.46 ⁵	0.30 ⁵
PDCB	PVC 0.98 ¹	0.95 ¹	0.95 ^{1,2}	0.94 ^{1,2}	0.91 ²	0.89 ²	0.75 ³
	PTFE 0.95 ¹	0.85 ²	0.76 ³	0.64 ³	0.51 ⁴	0.37 ⁴	0.26 ⁴
	FEP 0.95 ¹	0.84 ²	0.75 ³	0.66 ³	0.54 ³	0.43 ³	0.30 ⁴
	ABS 0.79 ²	0.36 ³	0.15 ⁵	0.07 ⁵	0.04 ⁶	0.03 ⁵	0.02 ⁶
	FRE 0.98 ¹	0.96 ¹	0.93 ²	0.90 ²	0.90 ²	0.91 ²	0.82 ²
	FRP 0.93 ¹	0.81 ²	0.69 ⁴	0.56 ⁴	0.46 ⁵	0.35 ⁴	0.20 ⁵
OXYL	PVC 0.98 ¹	0.97 ^{1,2}	0.97 ¹	0.99 ^{1,2}	0.97 ¹	0.97 ¹	0.93 ²
	PTFE 0.97 ¹	0.92 ²	0.89 ²	0.84 ³	0.77 ²	0.64 ³	0.52 ⁴
	FEP 0.98 ¹	0.92 ^{1,2}	0.88 ²	0.84 ³	0.78 ²	0.67 ³	0.56 ^{3,4}
	ABS 0.85 ²	0.54 ³	0.33 ³	0.16 ⁴	0.09 ³	0.05 ⁴	0.04 ⁵
	FRE 0.99 ¹	0.97 ^{1,2}	0.96 ¹	0.95 ²	0.98 ¹	0.97 ¹	0.95 ²
	FRP 0.97 ¹	0.91 ²	0.87 ²	0.83 ³	0.81 ²	0.72 ²	0.56 ³
MXYL	PVC 0.98 ¹	0.96 ^{1,2}	0.96 ¹	0.98 ^{1,2}	0.95 ²	0.95 ²	0.87 ³
	PTFE 0.96 ¹	0.89 ²	0.83 ²	0.74 ³	0.63 ⁴	0.48 ⁵	0.35 ⁵
	FEP 0.96 ¹	0.89 ²	0.82 ²	0.75 ³	0.66 ⁴	0.54 ⁴	0.41 ⁴
	ABS 0.83 ²	0.49 ³	0.27 ³	0.12 ⁴	0.08 ⁵	0.06 ⁶	0.05 ⁶
	FRE 0.99 ¹	0.96 ^{1,2}	0.96 ¹	0.94 ²	0.96 ²	0.98 ^{1,2}	0.93 ²
	FRP 0.97 ¹	0.89 ²	0.83 ²	0.77 ³	0.73 ³	0.63 ³	0.45 ⁴
MNT	PVC 0.99 ¹	1.00 ¹	0.99 ¹	1.00 ^{1,2}	0.99 ^{1,2}	0.98 ²	0.97 ²
	PTFE 1.00 ¹	0.99 ¹	0.98 ¹	0.98 ^{2,3}	0.96 ²	0.94 ³	0.90 ⁴
	FEP 1.00 ¹	0.99 ¹	0.98 ¹	0.98 ³	0.96 ²	0.94 ³	0.91 ⁴
	ABS 0.92 ¹	0.71 ³	0.52 ³	0.32 ⁵	0.19 ⁴	0.11 ⁵	0.07 ⁶
	FRE 1.00 ¹	0.99 ¹	0.98 ¹	0.98 ³	0.96 ²	0.97 ²	0.95 ³
	FRP 0.98 ¹	0.97 ²	0.93 ²	0.90 ⁴	0.85 ³	0.76 ⁴	0.64 ⁵

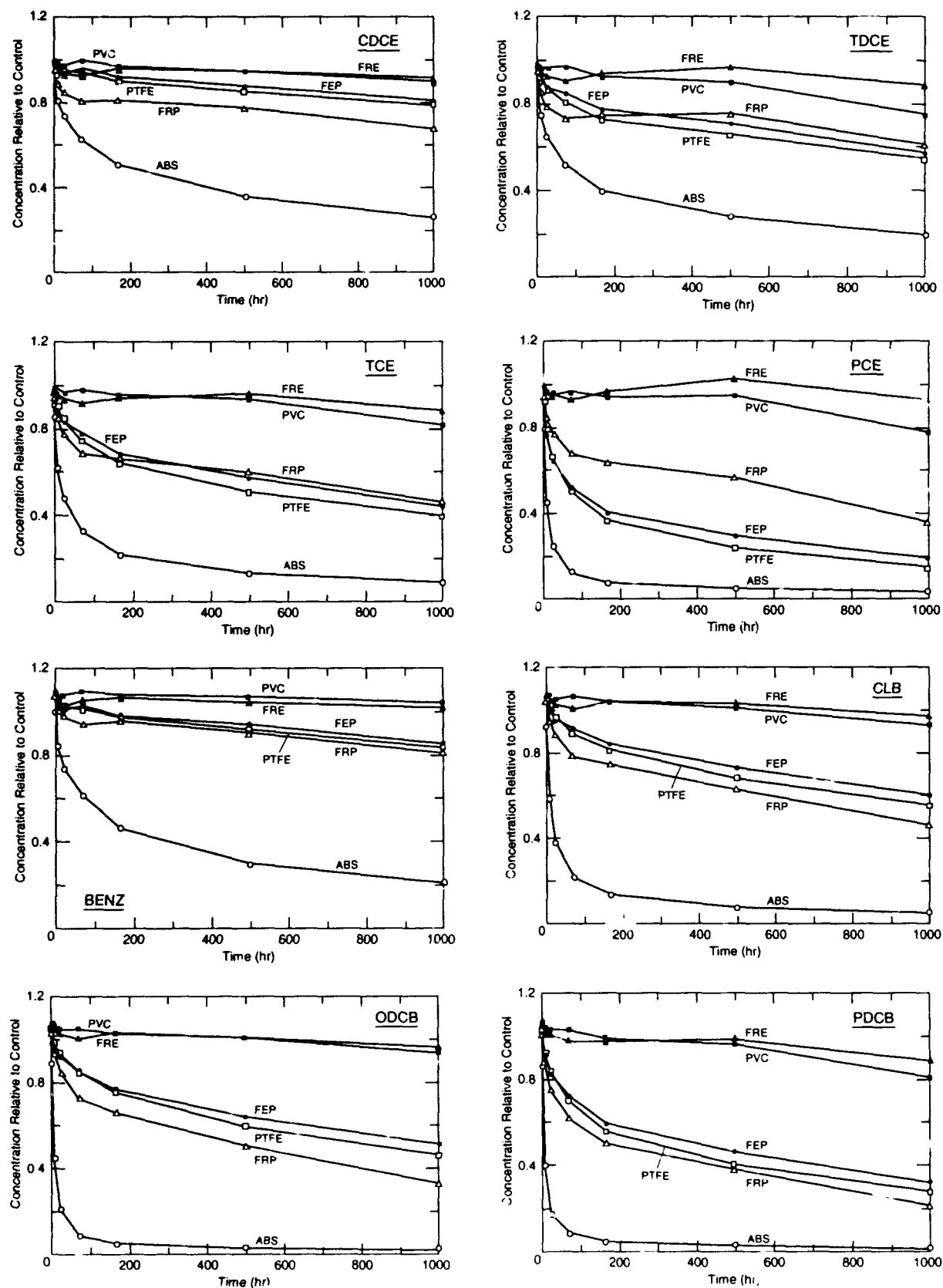


Figure 1. Sorption of the test materials.

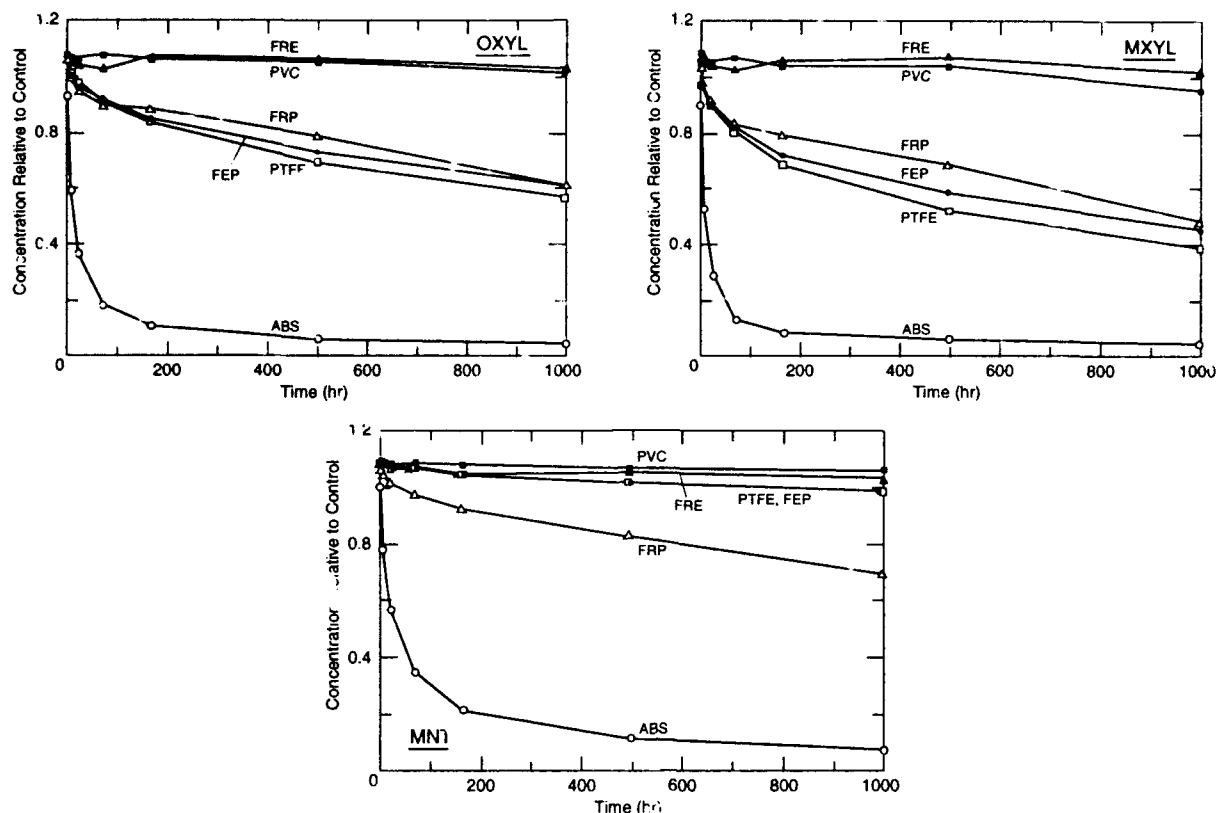


Figure 1 (cont'd). Sorption of the test materials.

materials had values that were significantly different from each other. The superscripts in Table 3 indicate when values were significantly different from each other and the controls.

During this study, we found that

- ABS always sorbed analytes the most rapidly and to the greatest extent of all the materials tested;
- PVC and FRE sorbed analytes the most slowly and to the least extent; and
- Neither PTFE, FEP nor FRP performed consistently better than each other.

Sorption by ABS was so rapid that after 1 hour, samples exposed to this casing were significantly lower than the controls for nine of the analytes (removal was 7–22%). After 1000 hours, loss ranged from 74 to 98%. For the least sorptive materials, PVC and FRE, loss ranged from 3 to 25% at 1000 hours. For the other materials (FEP, FRP and PTFE), there were statistically significant losses in 1–8 hours for some compounds. After 3 hours, analyte concentrations were significantly different from the controls for 10 of the 11 analytes for FRP, for 7 analytes for PTFE and for 6 analytes for FEP.

Table 4 gives the time required to see a 10% loss in analyte concentrations. For several organics, losses reached 10% in 8–24 hours for PTFE, FEP and

FRP and in 1–8 hours for ABS. This was not the case for PVC and FRE. For PVC the earliest a 10% loss was first observed was after 500 hours, and for FRE the earliest a 10% loss was observed was 72 hours. For several compounds, losses never reached 10%. This is especially true for FRE and PVC.

Our results generally agree well with those of Gillham and O'Hannesin (1990) except that they found that the rate and extent of sorption of the compounds they tested [(mono)aromatic hydrocarbons] were always greater for FRE than for PVC. Generally we did not find this to be the case in our study. By the end of the study, we found no significant difference between samples exposed to PVC vs. FRE for two of three compounds tested by Gillham and O'Hannesin (1990). Since both studies used a constant surface area/solution volume ratio (which differed between the two studies), we suspect that the reason they found more rapid loss with FRE than with PVC is because they tested FRE tubing and PVC pipe rather than well casings.

Leaching of contaminants

When we examined the HPLC chromatograms, we saw additional peaks in some of the samples when compared with the control samples (Fig. 2).

Table 4. Sampling time (hours) required for the material to sorb 10% or more of the analyte.

Material	CDCE	TDCE	TCE	PCE	BENZ	CLB	ODCB	PDCB	OXYL	MXYL	MNT
PVC	1000	500	1000	1000	NL*	1000	1000	500	NL	1000	NL
PTFE	168	24	8	8	168	24	24	8	24	8	1000
FEP	500	24	8	1	168	24	8	8	24	8	NL
ABS	8	1	1	1	8	1	1	1	1	1	8
FRE	NL	72 [†]	1000	NL	NL	1000	1000	72	NL	NL	NL
FRP	8	8	8	8	24	8	8	8	24	8	72

*Never lost 10% by the end of the study.

[†]Losses were only 7 and 4% at 168 and 500 hr., respectively.

By the end of the study, there were additional peaks in the chromatograms for the ABS, FRE and FRP samples but not for the FEP, PTFE and PVC samples. Of those samples that appeared to leach contaminants, the ABS samples appeared to leach the most, since these samples had the most peaks. The chromatogram for the last (1000-hour) samples had 11 additional peaks (Fig. 2). However, even the chromatograms for the 1-hour samples had one extra peak. The sizes of these peaks increased with time. The chromatograms for the FRP solutions had one additional peak after 72 hours and five additional peaks by the end of the study (Fig. 2). There was only one additional peak in the chromatograms for the FRE samples; this peak first appeared in the 72-hour samples. With both of the FRE and FRP samples, the sizes of the peaks increased with time.

To try to identify at least some of these peaks, we analyzed the 1000-hour samples by purge-and-trap GC/MS. When we analyzed the ABS sample, we observed six peaks and were able to identify four of them. This sample contained acrylonitrile and styrene (two of the three components of ABS), as well as chloroform and ethylbenzene (which is an intermediate in the production of styrene). The concentrations of these compounds in the sample were quite low (<10 µg/L). The other five peaks that we had observed previously in the HPLC chromatograms apparently were due to the presence of either non-volatile or semi-volatile organics or inorganic compounds (e.g. metal salts). We only found one peak when we ran the FRP sample, and this was determined to be toluene (which may be used as a solvent or degreaser in the production of FRP). The concentration of the toluene was approximately 100 µg/L. Again, the other four peaks that we observed previously in the HPLC chromatograms may be due to the presence of either non-volatile or semi-volatile organics or inorganic compounds. The one peak we observed in the HPLC chromatograms for the FRE samples is apparently not a

volatile organic, since we did not observe any peaks using purge-and-trap GC/MS on these samples. (This sample was run twice.) Based on Cowgill's (1988) findings, bisphenol A is a likely candidate.

We conducted a leaching study to confirm that the substances we found in the previous samples were in fact due to leaching from the casing material. To do this, we placed clean samples of FRE, FRP and ABS casings in well water, which contained HgCl₂ to prevent any biological activity. After 500 hours of contact time, the samples were also run by purge-and-trap GC/MS. We found essentially the same analytes in these samples as we did previously. The concentrations in these samples were fairly comparable to the 1000-hour samples, given the difference in contact time (500 vs. 1000 hr). We were able to identify two of five peaks we found in the chromatograms of ABS leachate: ethylbenzene and styrene. We did not find any spurious peaks in the FRE leachate sample. For the FRP leachate sample, we found five peaks and were able to identify three

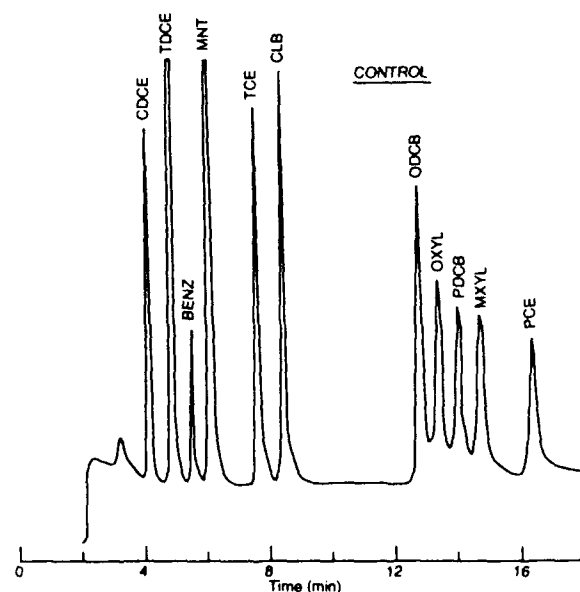


Figure 2. HPLC chromatograms for 1000-hour samples.

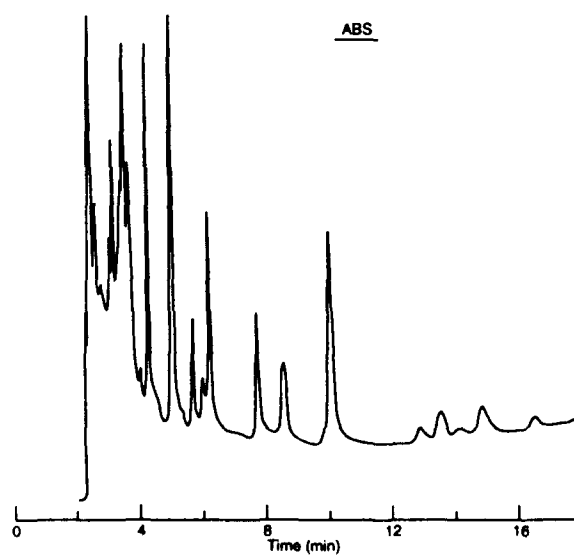
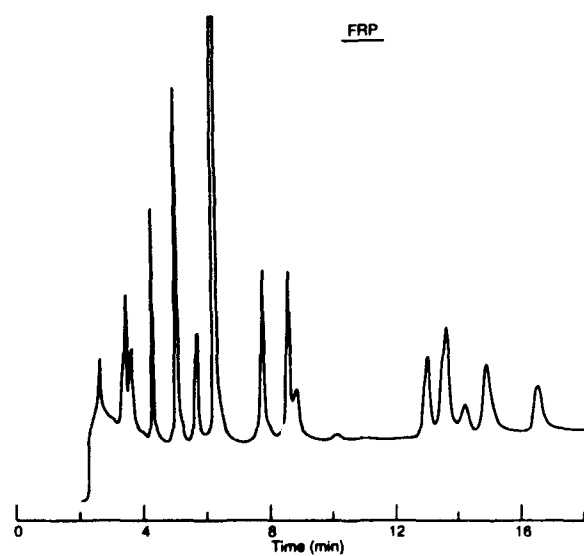
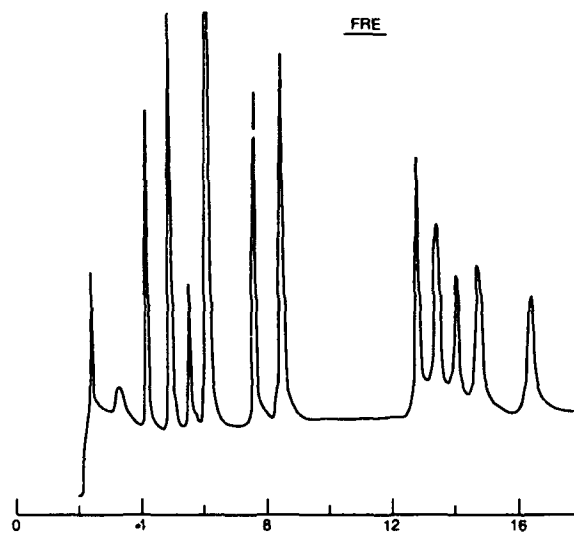
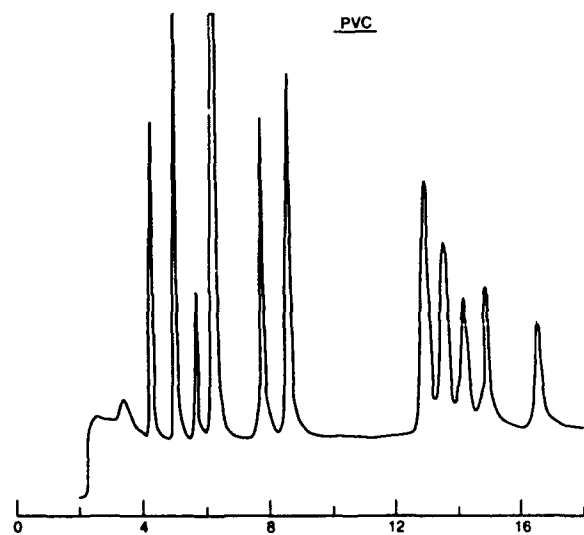
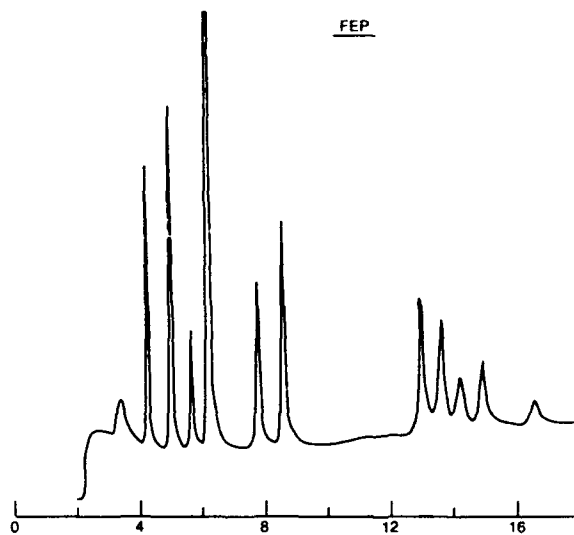
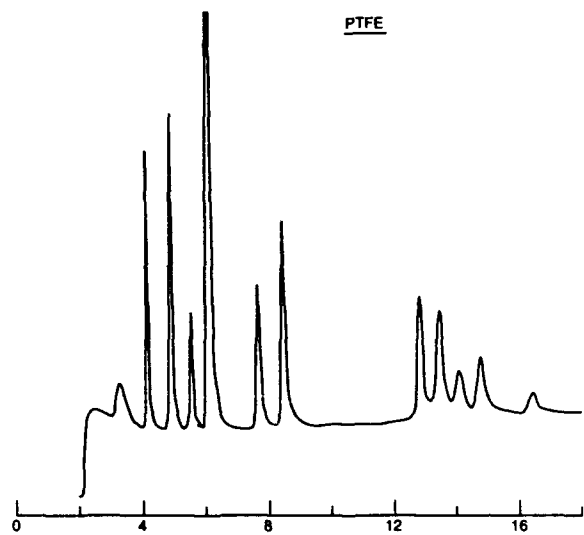


Figure 2 (cont'd).

of them. In addition to finding toluene again, we also found 1,1,1-trichloroethane and ethylbenzene. This particular sample was run twice, and both times we found the same analytes and in approximately the same concentrations. These solvents may be used in either manufacturing this product or cleaning some of the equipment used in its manufacture.

With respect to leaching of contaminants, our results agree well with what is found in the literature. Based on our literature review and the fact that we used a waste and vent pipe rather than well casing for monitoring groundwater, it is not surprising that we found some of the components used in manufacturing ABS (solvent or degreaser, component monomers and intermediates in the production of the monomer) leached from this product. As expected, FEP performed similarly to PTFE and did not show any signs of leaching any contaminants. Our results for FRE also agree well with those of Cowgill's (1988). We found evidence of only one compound leaching from this material; most likely this is the same component Cowgill observed leaching from ground FRE casing (bisphenol A).

FINAL CONCLUSIONS AND RECOMMENDATIONS

Based on the results from this study and those of Cowgill (1988), it appears that FRE would be an excellent candidate as an alternative material for monitoring organics. FEP appears to perform similarly to PTFE and at this time does not appear to offer any clear advantage or disadvantage over PTFE. (The cost of these two materials is also similar.) ABS sorbed organics very rapidly and leached several contaminants. Thus, this material would not be our first choice for a casing material that is to be used for monitoring organics. However, the waste and vent pipe we had to purchase for this study probably does not meet ASTM standards for well casings. Thus, well casings that meet ASTM standards may sorb organics less rapidly and leach fewer contaminants than the waste and vent pipe we tested.

For those materials that do sorb organics rapidly, once equilibrium is reached, sorption should no longer be of concern. However, purging the well may upset the equilibrium, and desorption of sorbed analytes could be a problem for some materials if groundwater quality were to improve.

Further research is needed to determine whether these materials sorb or leach metals. Further

studies on the leaching of organics from these materials should focus on non-volatiles and semi-volatiles and on the kinetics of the process to determine if leaching is only a surface phenomenon. In addition, further tests should be conducted to determine the ability of FRE and FRP well casings to withstand exposure to neat solvents. This research is needed to help determine the overall future usefulness of these materials to the groundwater monitoring industry. There is no compelling reason to study ABS further, especially since ABS well casings are no longer available.

LITERATURE CITED

- Aller, L., T.W. Bennett, G. Hackett, R.J. Petty, J.H. Lehr, H. Sedoris, D.M. Nielsen and J.E. Denne (1989) *Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells*. Dublin, Ohio: National Water Well Association.
- Barcelona, M.J., J.P. Gibb and R.A. Miller (1984) *A Guide to the Selection of Materials for Monitoring Well Construction and Ground Water Sampling*. U.S. Environmental Protection Agency, Report No. EPA-600/2-84-024. Washington, D.C.: U.S. Government Printing Office.
- Barcelona, M.J., J.A. Helfrich and E.E. Garske (1985) Sampling tubing effects on ground water samples. *Analytical Chemistry*, 57:460-464.
- Cole-Parmer Instrument Company (1992) *Cole-Parmer Instrument Company 1993-1994 Catalogue*. Niles, Illinois: Cole-Parmer Instrument Company.
- Cowgill, U.M. (1988) The chemical composition of leachate from a two-week dwell-time study of PVC casing and a three-week dwell time study of fiberglass reinforced epoxy well casing. In *Ground-Water Contamination: Field Methods*, ASTM STP 963 (A.G. Collins and A.I. Johnson, Ed.), p. 172-184. Philadelphia, Pennsylvania: American Society for Testing and Materials.
- Curran, C.M and M.B. Tomson (1983) Leaching of trace organics into water from five common plastics. *Groundwater Monitoring Review*, 3: 68-71.
- Driscoll, F.G. (1986) *Ground Water and Wells*. St. Paul, Minnesota: Johnson Filtration Systems, Inc.
- Fuchs, O. (1989) Solvents and non-solvents for polymers. In *Polymer Handbook*, Third Edition (J. Brandrup and E.H. Immergut, Ed.). New York, N.Y.: John Wiley and Sons, Inc.
- Gillham, R.W. and S.F. O'Hannesin (1990) Sorption of aromatic hydrocarbons by materials used in construction of ground-water monitoring sampling wells. In *Ground Water and Vadose Zone Monitoring*, ASTM STP 1053 (D.M. Nielsen and A.I. Johnson,

- Ed.). Philadelphia, Pennsylvania: American Society for Testing and Materials, p. 108-122.
- Hewitt, A.D.** (1989) Leaching of metal pollutants from four well casings used for groundwater monitoring. USA Cold Regions Research and Engineering Laboratory, Special Report 89-32.
- Hewitt, A.D.** (1992) Potential of common well casing materials to influence aqueous metal concentrations. *Ground Water Monitoring Review*, 12(2): 131-135.
- Hiemenz, P.C.** (1986) *Principles of Colloid and Surface Chemistry*, Second Edition. New York, N.Y.: Marcel Dekker, Inc.
- Jones, J.N. and G.D. Miller** (1988) Adsorption of selected organic contaminants onto possible well casing materials. In *Ground Water Contamination: Field Methods*, ASTM STP 963 (A.G. Collins and A.I. Johnson, Ed.). Philadelphia, Pennsylvania; American Society for Testing and Materials, p. 185-198.
- Masse, R., F.J.M.J. Maessen and J.J.M. DeGoeij** (1981) Loss of silver, arsenic, cadmium, selenium and zinc traces from distilled water and artificial sea-water by sorption on various container surfaces. *Analytica Chimica Acta*, 127: 181-193.
- Miller, G.D.** (1982) Uptake and release of lead, chromium, and trace level volatile organics exposed to synthetic well casings. In *Proceedings of the Second National Symposium on Aquifer Restoration and Ground Water Monitoring*. National Water Well Association, U.S. Environmental Protection Agency, and National Center for Ground Water Research.
- Nielsen, D.M. and R. Schalla** (1991) Design and installation of ground-water monitoring wells. In *Practical Handbook of Ground-Water Monitoring* (D.M. Nielsen, Ed.). Chelsea, Michigan: Lewis Publishers, p. 239-331.
- Parker, L.V., A.D. Hewitt and T.F. Jenkins** (1990) Influence of casing materials on trace-level chemicals in well water. *Ground Water Monitoring Review*, 10(2): 146-156.
- Raber, E., J. Garrison and V. Oversby** (1983) The sorption of selected radionuclides on various metal and polymeric materials. *Radioactive Waste Management and the Nuclear Fuel Cycle*, 4(1): 41-52.
- Reynolds, G.W. and R.W. Gillham** (1986) Adsorption of halogenated organic compounds by polymer materials commonly used in groundwater monitors. In *Proceedings of Second Canadian/American Conference on Hydrogeology, Hazardous Wastes in Ground Water: A Soluble Dilemma*. Dublin, Ohio: National Water Well Association, p. 125-132.
- Reynolds, G.W., J.T. Hoff and R.W. Gillham** (1990) Sampling bias caused by materials used to monitor halocarbons in groundwater. *Environmental Science and Technology*, 24(1): 135-142.
- Sax, N.I. and R.J. Lewis Sr.** (1987) *Hawley's Condensed Chemical Dictionary*, Eleventh Edition. New York, N.Y.: Van Nostrand Reinhold Company.
- U.S. EPA** (1986) *Test Methods for Evaluating Solid Waste. Volume 1B: Laboratory Manual Physical/Chemical Methods*, Third Edition. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. 20460. NTIS# PB88-239223, Part 2 of 4, National Technical Information Service, Springfield, Virginia.
- U.S. EPA** (1992) *EPA RCRA Ground-Water Monitoring: Draft Technical Guidance*. EPA/530-R-93-001, Office of Solid Waste, U.S. Environmental Protection Agency, Washington, D.C. 20460. NTIS #PB 93-139-350, National Technical Information Service, Springfield, Virginia.

**APPENDIX A. CHEMICAL RESISTANCE OF VARIOUS MATERIALS TO
SELECTED CHEMICALS
(COURTESY OF COLE-PARMER INSTRUMENT COMPANY)**

The Cole-Parmer Catalog includes the following disclaimer: "These chemical resistance charts rate the effect of corrosive chemicals on various materials. Use these charts as a general guide, not an unqualified guarantee of chemical compatibility. Cole-Parmer® can assume no responsibility for the use of this information in specific applications. Test only under specified conditions of your application to ensure safe use of a chemical. Immersion testing methods are preferred for more accurate test results." This table includes most but not all of the chemicals given in the Cole-Parmer catalog (Cole-Parmer 1992). Additional materials are also given in this reference.

Ratings—Chemical Effect;

A—No effect; Excellent; B—Minor effect; Good; C—Moderate effect; Fair; D—Severe effect; Not Recommended

Chemical	Plastics				Metals	
	ABS	Epoxy	PTFE (Teflon®)	PVC	304 Stainless steel	316 Stainless steel
Acetaldehyde	D	A	A	D	A	A
Acetic Acid	D	C	A	D	D	B
Acetic Acid 20%	C	A ¹	A	D	B	A
Acetic Acid 80%	D	B ¹	A	C	D	B
Acetic Acid, Glacial	D	B ¹	A	D	C	A
Acetone	D	B ¹	A	D	A	A
Acrylonitrile	D	A	A	B ¹	A ¹	A ¹
Alcohols						
Amyl	A ¹	B ²	A	A ²	A	A
Benzyl	D	C	A	D	B	B
Butyl	A ¹	A/D*	A/A ² *	A ² /C ¹ *	A	A ¹ *
Diacetone	—	A	A	B ¹ /D*	A	A
Ethyl	B ¹	A ²	A	C	A	A
Hexyl	—	A	A	A ²	A	A
Isobutyl	B	A	A ²	A ¹	A	A
Isopropyl	—	A	A ²	A ¹	B	B
Methyl	D	B ¹	A	A ¹	A	A
Octyl	A ¹	A	—	—	A	A
Propyl	B ¹	A	A	A ¹	A	A
Aluminum Chloride	A	A ¹	A	A ²	B	B
Aluminum Chloride 20%	—	A ¹	A	A ¹	D	C ¹
Aluminum Fluoride	A	B ¹	A	A ²	D	D
Aluminum Hydroxide	B	B ¹	A	A ²	A ¹	C ¹
Aluminum Nitrate	—	A ²	A	B ²	A	A
Aluminum Potassium Sulfate 10%	—	A ¹	A	A ²	A	A
Aluminum Potassium Sulfate 100%	—	A ¹	A	A ²	D	B ¹
Aluminum Sulfate	A ²	A ²	A	A ²	B	B ²
Amines	—	A ²	A ²	D	A	A
Ammonia 10%	—	A ²	A	B ¹	A	A
Ammonia Nitrate	—	A	A	B	A	A
Ammonium Chloride	A ²	A ¹	A	A ²	C	B ²
Ammonium Hydroxide	B	A ¹	A	A	A ¹	A ¹
Ammonium Nitrate	—	A ²	A	A ²	A ¹	A
Ammonium Sulfate	A ²	A ²	A	A ²	B	B
Amyl Acetate	D	A ²	A	D	A ¹	A
Aniline	D	D	A	C ¹	A	B
Antifreeze	B	A	—	A	—	A
Antimony Trichloride	A ²	D	A	A ²	D	D

¹ Satisfactory to 72° F (22°C).

² Satisfactory to 120° F (48°C).

* Different ratings were given depending on where in the document the chemical was listed.

Chemical	Plastics				Metals	
	ABS	Epoxy	PTFE (Teflon®)	PVC	304 Stainless steel	316 Stainless steel
Arochlor 1248	—	A ²	A	—	B	B
Arsenic Acid	A ²	A ²	A	A ¹	A ²	A ²
Arsenic Salts	—	—	—	A	—	—
Asphalt	—	A	A ¹	A ²	B	A
Barium Carbonate	A ²	A ²	A	A ²	B ¹	B
Barium Chloride	A ²	A ²	A	A ¹	A ¹	A ¹
Barium Cyanide	—	A	A ¹	D	A ¹	A ²
Barium Hydroxide	A ²	A ²	A	A ²	B ¹	B
Barium Nitrate	—	A ¹	A ¹	A	B ¹	B
Barium Sulfate	A ²	A ²	A	B ¹	B ¹	B ¹
Barium Sulfide	A ²	B ²	A	A ²	B ¹	B ²
Benzaldehyde	B	D	A ¹	D	B	B
Benzene	D	C ¹	A	C ¹	B	B
Benzene Sulfonic Acid	—	B	A	A	B	B
Benzoic Acid	—	A ¹	A ²	A	B	B
Benzonitrile	—	—	A ²	—	D	D
Benzyl Chloride	D	—	—	—	C ¹	B ¹
Boric Acid	—	A ¹	A	A ²	B ²	A ¹
Bromine	D	D	A	C ¹	D	D
Butadiene	—	A ¹	A ²	C ¹	A	A ¹
Butyl Amine	—	B ²	A ²	D	—	A
Butyl Ether	—	A ¹	A ¹	A ²	—	A ¹
Butyl Phthalate	—	B ²	A ²	—	B ¹	B ²
Butylacetate	—	B ¹	A	D	B	A
Butylene	—	A ¹	A	A ¹	A	A
Butyric Acid	D	A	A ²	B ¹	B ²	B ²
Calcium Bisulfate	—	A	—	—	—	A
Calcium Bisulfide	—	A	A	A ²	B	B
Calcium Bisulfite	—	A ¹	A	B	B	A
Calcium Carbonate	—	A ¹	A	A ²	A ¹	B
Calcium Chloride	B	A ¹	A	C	C ²	B ²
Calcium Hydroxide	—	A ¹	A	B	B ¹	B
Calcium Hypochlorite	—	A ¹	A	B ¹	C ¹	B ¹
Calcium Nitrate	A	A ²	A ²	A ²	C ¹	B ²
Calcium Sulfate	C	A ²	A	B ²	B	B
Carbon Bisulfide	—	A	—	D	A	B
Carbon Disulfide	—	C ¹	A	D	A ¹	B
Carbon Tetrachloride	D	A ¹	A	D	B	B
Carbonic Acid	—	A ²	A	A ²	A ¹	A
Chloric Acid	—	—	A	A ²	D	C ¹
Chloroacetic Acid	—	C ¹	A	B ¹	B ¹	A ¹
Chlorobenzene (Mono)	D	C ¹	B	D	A	B
Chlorobromomethane	—	—	A	D	—	—
Chloroform	D	C ¹	A ¹	D	A	A
Chlorosulfonic Acid	—	C ¹	A ¹	D	D	B ²
Chromic Acid 10%	B	D	A	A ²	B	B
Chromic Acid 50%	D	D	A	D	C	B ²
Chromium Salts	—	—	—	A	—	—
Citric Acid	D	A ¹	A	B ²	B ¹	A ²
Clorox®(Bleach)	B	D	A	A	A	A
Copper Chloride	A	A	A	A ¹	D	D
Copper Cyanide	—	B ¹	A	A ²	B	B
Copper Fluoborate	—	A	—	A	D	D
Copper Nitrate	—	A ¹	A	A ²	A	A ²
Copper Sulfate 5%	—	A	A	A ²	B	B
Copper Sulfate >5%	—	A	A	A ²	B	B
Cresols	D	A ¹	—	D	A ²	A
Cresylic Acid	—	D	A	D	A ¹	A

¹ Satisfactory to 72° F (22°C). ² Satisfactory to 120° F (48°C).

Chemical	Plastics				Metals	
	ABS	Epoxy	PTFE (Teflon®)	PVC	304 Stainless steel	316 Stainless steel
Cupric Acid	—	A ²	A	A ²	D	B ²
Cyanic Acid	—	A ¹	A	—	A	A
Cyclohexane	—	A ²	A	D	A ¹	A
Cyclohexanone	D	C	A	D	A ¹	A ²
Detergents	B	A ¹	A	A	A ¹	A ¹
Dichlorobenzene	D	A	A	D	—	B ¹
Dichloroethane	D	D	A ¹	D	B	B
Diesel Fuel	—	A	A	A ¹	A ¹	A ¹
Diethyl Ether	D	D	A	D	B ¹	B ²
Diethylamine	D	A	D	D	A	A
Diethylene glycol	B	C	A ²	C ¹	A ¹	A
Dimethyl Aniline	D	A ¹	A	D	B ²	B ²
Dimethyl Formamide	D	D	D	D	A	B
Diphenyl	—	—	A	—	B	B
Diphenyl Oxide	—	A	A ¹	D	B ¹	A
Ethanolamine	—	A ¹	A ¹	D	A	A
Ether	D	A ¹	A	D	A	A
Ethyl Acetate	D	A	A	D	B	B
Ethyl Benzoate	D	—	A	D	—	—
Ethyl Chloride	D	D	A	D	A	A
Ethyl Ether	D	A ²	A	D	B	B
Ethyl Sulfate	—	A ¹	A	—	D	D
Ethylene Bromide	D	—	A	D	A	A
Ethylene Chloride	D	D	A	D	B	B
Ethylene Chlorohydrin	D	D	A	D	B	B
Ethylene Diamine	D	A ¹	A	D	B ¹	B
Ethylene Dichloride	D	D	A	D	B	B
Ethylene Glycol	A	A	A	A	B	B
Ethylene Oxide	D	D	A	D	B	B
Ferric Chloride	A	A	A	A	D	D
Ferric Nitrate	A ²	A	A	A	B	B
Ferric Sulfate	A ²	A	A	A	B ¹	A
Ferrous Chloride	A ²	A	A	A	D	D
Ferrous Sulfate	A ¹	A	A	A	B	B
Fluoboric Acid	A ²	D	A	A	B	B
Fluosilicic Acid	A ²	C	A	D	C	B
Formaldehyde 40%	A ²	A ²	A	A	A ¹	A
Formaldehyde 100%	B	A	A	A	C	A
Formic Acid	D	C ¹	A	A ¹	B ¹	A ¹
Freon® 11	D	A	A	A ²	A	A
Freon® 12	A ¹	A ²	A	A ²	B ¹	B
Freon® 22	—	A	A	A	A	A
Freon® 113	—	A	A	B	—	—
Freon® TF	—	A	A	B	A	A
Fuel Oils	D	A ¹	B	A ²	A	A
Furfural	D	A ¹	A	D	A	B
Gallic Acid	—	—	B	B	A	B
Gasoline (high-aromatic)	D	A	B	A	A	A
Gasoline, leaded, ref.	D	A ²	A	B	A ¹	A ²
Gasoline, unleaded	D	A ²	A	C ²	A ¹	A ²
Heptane	D	A	A	C ¹	A	A
Hexane	D	A	A	B ¹	A	A
Hydraulic Oil (Petro)	—	A	A	A	A	A
Hydraulic Oil (Synthetic)	—	A	A	A	A	A
Hydrazine	—	A	C	—	A	A
Hydrobromic Acid 20%	—	B ¹	—	B ²	D	D
Hydrobromic Acid 100%	B	D	A	A ¹	D	D
Hydrochloric Acid 20%	A	A ¹	A	A ²	D	D
Hydrochloric Acid 37%	A	A	A	B	D	D
Hydrochloric Acid 100%	A	—	A	D	D	D

Chemical	Plastics				Metals	
	ABS	Epoxy	PTFE (Teflon®)	PVC	304 Stainless steel	316 Stainless steel
Hydrochloric Acid, Dry Gas	—	A	A	A ²	D	D
Hydrocyanic Acid	B	A	A	B	B ¹	A
Hydrofluoric Acid 20%	C	A	A	B	D	D
Hydrofluoric Acid 50%	C	C ²	A	B ¹	D	D
Hydrofluoric Acid 75%	C	B ¹	A	C	D	D
Hydrofluoric Acid 100%	D	—	A	C	B ¹	B ¹
Hydrofluosilicic Acid 20%	—	C ¹	A	A ²	C ²	B ¹
Hydrofluosilicic Acid 100%	—	C ¹	A	B ¹	D	D
Hydrogen Peroxide 10%	A	C ¹	A	A ¹	B ²	B
Hydrogen Peroxide 30%	—	B	A	A ¹	B ²	B
Hydrogen Peroxide 50%	—	—	A	A ¹	B ²	A ²
Hydrogen Peroxide 100%	A	A	A	A	B ²	A
Hydrogen Sulfide (aqua)	B	A	A	B ¹	C	A
Hydrogen Sulfide (dry)	—	A	A	A ²	C ¹	A
Hydroquinone	D	—	A	B	B	B
Hydroxyacetic Acid 70%	—	A	A	D	—	—
Iodine	D	C	A	A	D	D
Isooctane	—	A ²	A	A ¹	A ¹	A ¹
Isopropyl Acetate	—	A	A	D	C	A
Isopropyl Ether	—	D	A ¹	B	A	A
Jet Fuel (JP3, JP4, JP5)	—	A	A	C	A	A
Kerosene	D	A	A	A ²	A	A
Ketones	A	C	A	D	A	A
Lacquer Thinners	A	A	A	D	A ¹	A
Lacquers	A	A	A	D	A ¹	A
Lactic Acid	D	B ¹	A	B ¹	B ¹	B ¹
Latex	B	A	A	—	A ²	A ²
Lead Acetate	B	A	A	B	B	B ¹
Lead Nitrate	B	—	A ¹	A ²	B ¹	B ¹
Lead Sulfamate	—	A	B	B	C	C
Lime	—	A	A ¹	B	A	A
Lithium Chloride	—	—	A	D	A ¹	A ²
Lithium Hydroxide	—	—	A	—	B	B
Lubricants	—	A	A	B ²	A ²	A ²
Lye: Potassium Hydroxide	A	A	A	B	B	A ¹
Lye: Sodium Hydroxide	C	A	A	A	B	B ¹
Lye: Calcium Hydroxide	—	A ¹	A	B ²	B ¹	B
Magnesium Bisulfate	—	—	A	A ²	A ¹	A ¹
Magnesium Chloride	B	A	A	B	D	D
Magnesium Hydroxide	B	A	A	A ²	B	A ¹
Magnesium Nitrate	B	A	A	A ²	B	B
Manganese Sulfate	B ²	—	A	C	B	B ²
Mercuric Chloride (dilute)	B	A	A	A	D	D
Mercuric Cyanide	B	A	B	A	C	C
Mercurous Nitrate	C ²	—	A	A	A ¹	A ¹
Mercury	B	A	A	A	A	A
Methyl Acetate	D	D	A	D	A	B
Methyl Acetone	—	C	A	D	A	A
Methyl Acrylate	—	A	—	—	A	—
Methyl Bromide	D	B	A	D	A	A
Methyl Butyl Ketone	—	C	—	A	A	A
Methyl Cellosolve	—	C	A	D	B	B
Methyl Chloride	D	A	A	D	A	A
Methyl Dichloride	—	A	—	A	—	—
Methyl Ethyl Ketone	D	C ¹	A	D	A	A
Methyl Isobutyl Ketone	D	C	A	D	B	B
Methyl Isopropyl Ketone	—	A	A	D	A	A
Methyl Methacrylate	—	A	—	A	B	B

¹ Satisfactory to 72° F (22°C). ² Satisfactory to 120° F (48°C).

Chemical	Plastics				Metals	
	ABS	Epoxy	PTFE (Teflon®)	PVC	304	316
					Stainless steel	Stainless steel
Methylamine	D	A	A	D	A	A
Methylene Chloride	D	A	A	D	B	B
Mineral Spirits	D	A	A	A	A	A
Monochloroacetic acid	—	—	A ²	—	A ¹	A ¹
Monoethanolamine	—	A	A	D	A	A
Morpholine	C	—	A ²	—	—	A ¹
Motor Oil	C	—	A	B	A ¹	A ²
Naphtha	D	A	B	A ¹	A	A
Naphthalene	D	A	A	D	A	A
Natural Gas	B	—	A	A	A	A
Nickel Chloride	A	A	A	A	D	C
Nickel Nitrate	A	A ¹	A ²	A	B	B ²
Nickel Sulfate	B	A	A	A	B	B ¹
Nitrating Acids (≤1% Acid)	—	—	A	D	C	A
Nitrating Acids (≤15% H ₂ SO ₄)	—	—	A	D	C	C
Nitrating Acids (≥15% H ₂ SO ₄)	—	D	A	D	C	C
Nitrating Acid (≤15% HNO ₃)	—	—	A	D	C	D
Nitric Acid (5–10%)	B	A ¹	A	A ¹	A	A
Nitric Acid (20%)	B	B ¹	A	A ¹	A	A
Nitric Acid (50%)	C	D	A	B ¹	A ²	A ¹
Nitric Acid (Concentrated)	D	D	A	B ¹	A ¹	A ¹
Nitrobenzene	D	C ¹	A	D	B	B
Nitromethane	D	—	A	B ²	A	A ¹
Oils: Aniline	D	A	A	D	A	A
Bone	—	A	A	—	—	A
Castor	A	A	A	A	A	A
Creosote	—	A	A	C	B	B
Diesel Fuel (20, 30, 40, 50)	—	A ¹	A	B	A	A
Fuel (1, 2, 3, 5A, 5B, 6)	D	A ¹	A	A ²	A	A
Hydraulic Oil (Petro)	—	A	A	A	A	A
Hydraulic Oil (Synthetic)	—	A	A	A	A	A
Mineral	A	A	A	B	A	A
Pine	D	A	A	D	A	A
Rosin	—	A	A	C ¹	A ¹	A ¹
Silicone	A	A	A	A	A	A
Transformer	—	B	A	B	A	A
Turbine	—	A	A	A ¹	A	A
Oleic Acid	D	A	A	C ²	A	A
Oxalic Acid (cold)	A	A	A ¹	B	B	A
Palmitic Acid	A	A	A ²	B ¹	B ¹	A ¹
Paraffin	A	A	A	B	A	A
Pentane	—	A	A	A	C	C
Perchloric Acid	—	—	A	C	C	C
Perchloroethylene	D	D	A	C ¹	B	A ¹
Petroleum	B	A ²	A ²	—	A ¹	A ¹
Phenol (10%)	D	C	A	C ¹	B	B
Phenol (Carbolic Acid)	D	C	A	D	B	B
Phosphoric Acid (≤ 40%)	B	A	A	B	D	C
Phosphoric Acid (> 40%)	C	B	A	B	D	D
Phosphoric Acid (crude)	C	B	A	B ²	D	B
Phthalic Acid	B	—	A ²	—	B ²	A
Phthalic Anhydride	B	—	A	D	A	A
Picric Acid	A	A	A	D	B	B
Potash (Potassium Carbonate)	A	A	—	A	B	B
Potassium Bicarbonate	A	A	A	A	B	B
Potassium Bromide	A ¹	A	A	A	B	B
Potassium Chlorate	A	A	A	A	B ¹	B
Potassium Chloride	A	A	A	A	B ¹	A ¹
Potassium Chromate	—	C	A ¹	A	B ¹	B ¹
Potassium Cyanide Solutions	A	A	A	A	B ¹	B ¹

Chemical	Plastics				Metals	
	ABS	Epoxy	PTFE (Teflon®)	PVC	304	316
					Stainless steel	Stainless steel
Potassium Dichromate	B ¹	C	A	A	B	B ¹
Potassium Ferricyanide	B	A ¹	A ²	A	B ¹	B ¹
Potassium Ferrocyanide	—	A	A	A	B	B
Potassium Hydroxide (Caustic Potash)	A	A	A	A ¹	B	A ¹
Potassium Hypochlorite	—	—	A ²	B ¹	C ¹	B
Potassium Nitrate	B	A	A	A	B	B
Potassium Oxalate	—	—	A ²	—	B	B ¹
Potassium Permanganate	B ¹	A	A	A ¹	B ¹	B
Potassium Sulfate	B	A	A	A ²	B ¹	A
Potassium Sulfide	B	—	A	A ²	B	B
Propylene Glycol	B	B	A	C ¹	B	B
Pyridine	—	A	A	D	A	A
Pyrogalllic Acid	—	A	A	A	B ²	B
Resorcinol	A	—	A ²	C	—	—
Salt Brine (NaCl saturated)	—	A	A ²	A	B ¹	A ²
Sea Water	—	A	A	A ²	C	C
Silicone	D	A	A	A	A	A
Silver Bromide	—	A	A	—	D	D
Silver Nitrate	B	A	A	A ¹	B	B
Soda Ash (see Sodium Carbonate)	B	C	A	A	A	A
Sodium Acetate	B	A	A	B ¹	B	B ¹
Sodium Aluminate	—	A	A	—	A	A
Sodium Benzoate	A	A ²	A ²	B ¹	—	—
Sodium Bicarbonate	A	A	A	A ²	A	A ¹
Sodium Bisulfate	A	A	A	A ²	D	C
Sodium Bisulfite	A	A	A	A ²	B ¹	B ¹
Sodium Borate	A	A	A	A ²	B ²	B
Sodium Bromide	B	A	A ²	B ²	C	C
Sodium Carbonate	B	C ¹	A	A ²	A	A
Sodium Chlorate	A	A	A	A ¹	A	B ¹
Sodium Chloride	A	A	A	A ²	B	B
Sodium Chromate	—	C	A	—	B ¹	B
Sodium Cyanide	A	A	A	A ²	A ¹	B ¹
Sodium Ferrocyanide	—	A	A	A	B	B
Sodium Fluoride	A	A	A ¹	A ²	D	D
Sodium Hydrosulfite	—	—	A	C	—	—
Sodium Hydroxide (20%)	B	A ²	A	A	B	B ²
Sodium Hydroxide (50%)	A	A	A	A	B	B ¹
Sodium Hydroxide (80%)	A	A ¹	A ¹	A	C	B ¹
Sodium Hypochlorite (100%)	—	D	A	B	D	D
Sodium Hypochlorite (<20%)	B	C	A	A	C	C
Sodium Nitrate	—	A	A	A ²	B ¹	B ¹
Sodium Peroxide	—	C	A	B ²	A	A
Sodium Sulfate	—	A	A	A ²	B	B ¹
Sodium Sulfide	—	A	A	A ²	B	D
Sodium Sulfite	—	A	A	A ²	B	A
Sodium Thiosulfate (hypo)	—	A	A	A ²	A ²	B
Stannic Chloride	—	A	A	A ²	D	D
Stannic Fluoborate	—	A	—	—	—	A
Stannous Chloride	—	A	A	A ¹	C ²	A ²
Stearic Acid	—	B	A	B ²	B	A
Stoddard Solvent	B	A	A	C ¹	A	A
Styrene	—	A	A	D	A	A
Sulfur Chloride	—	C	A	C ¹	D	D
Sulfur Dioxide	D	A ¹	A	A ¹	D	A ¹
Sulfuric Acid (10–75%)	B	A ¹	A	A ¹	D	D
Sulfuric Acid (75–100%)	—	C ¹	A	D	C	D
Sulfuric Acid (<10%)	B	A ¹	A	A ¹	D	B

¹ Satisfactory to 72° F (22°C). ² Satisfactory to 120° F (48°C).

Chemical	Plastics				Metals	
	ABS	Epoxy	PTFE (Teflon®)	PVC	304 Stainless steel	316 Stainless steel
Sulfurous Acid	—	A	A	A ²	B ¹	B
Sulfuryl Chloride	—	A	A	—	—	—
Tannic Acid	—	A	A	A ¹	B ¹	A
Tartaric Acid	—	A	A	A ¹	C ²	C ²
Tetrachloroethane	—	A	A	C	B	A
Tetrachloroethylene	—	—	A	D	—	A
Tetrahydrofuran	—	A	A	D	A	A
Tin Salts	—	—	A	A	—	D
Toluene (Toluol)	D	B ¹	A	D	A	A
Trichloroacetic Acid	—	D	A	B	D	C
Trichloroethane	—	A	A	C	B	B
Trichloroethylene	D	C ¹	A	D	B	B
Trichloropropane	D	A	A ¹	—	A	A
Tricresylphosphate	B	A	A	D	B	B
Triethylamine	—	A	A	B	A	A
Trisodium Phosphate	B ¹	A	A	A	B	B
Turpentine	D	B ¹	A	D	A	A
Urea	B	—	A	D	B	B
Uric Acid	—	—	A	A	B	B
Vinyl Acetate	—	A ¹	A ²	D	B	B
Vinyl Chloride	D	—	A ²	D	B ²	A ¹
Water, Deionized	—	A ²	A ²	A ²	A ¹	A ²
Water, Acid, Mine	B	A	A	B	B	B
Water, Distilled	B	A	A	A ²	A	A
Water, Fresh	A	A	A	B	A	A
Water, Salt	—	A	A	B	B	B
Weed Killers	—	A	—	—	A	A
Xylene	D	A	A	D	B	B
Zinc Chloride	A	A	A	B	B	B
Zinc Hydrosulfite	A	A	A	—	A	A
Zinc Sulfate	A	A	A	A	B ¹	A

**APPENDIX B: CONCENTRATION OF ANALYTES (mg/L)
AND RELATIVE STANDARD DEVIATIONS FOR THE
11 ORGANIC COMPOUNDS TESTED**

CDCE

<i>Treatment*</i>	<i>1 hr</i>	<i>8 hr</i>	<i>24 hr</i>	<i>72 hr</i>	<i>168 hr</i>	<i>500 hr</i>	<i>1000 hr</i>
Control	1.74	1.66	1.74	1.74	1.71	1.25	1.59
Control	1.67	1.69	1.81	1.72	1.68	1.26	1.60
Control	1.66	1.61	1.77	1.75	1.65	1.23	1.54
$\bar{X} \pm s$	1.69±0.044	1.65±0.04	1.77±0.035	1.74±0.015	1.68±0.03	1.25±0.015	1.58±0.032
RSD (%)	2.6	2.4	2.0	0.9	1.8	1.2	2.0
PVC	1.72	1.67	1.76	1.71	1.65	1.20	1.45
PVC	1.63	1.62	1.73	1.73	1.61	1.16	1.42
PVC	1.63	1.57	1.69	1.71	1.62	1.16	1.39
$\bar{X} \pm s$	1.66±0.052	1.62±0.05	1.73±0.035	1.72±0.012	1.63±0.021	1.17±0.023	1.42±0.03
RSD (%)	3.1	3.1	2.0	0.7	1.3	2.0	2.1
PTFE	1.72	1.62	1.72	1.63	1.55	1.08	1.28
PTFE	1.71	1.62	1.65	1.61	1.50	1.05	1.22
PTFE	1.59	1.48	1.66	1.60	1.50	1.06	1.25
$\bar{X} \pm s$	1.67±0.072	1.57±0.081	1.68±0.038	1.61±0.015	1.52±0.029	1.06±0.015	1.25±0.03
RSD (%)	4.3	5.1	2.3	0.9	1.9	1.4	2.4
FEP	1.75	1.66	1.65	1.63	1.57	1.09	1.28
FEP	1.67	1.62	1.65	1.67	1.55	1.10	1.28
FEP	1.64	1.49	1.70	1.63	1.51	1.09	1.26
$\bar{X} \pm s$	1.69±0.057	1.59±0.089	1.67±0.029	1.64±0.023	1.54±0.031	1.09±0.006	1.27±0.012
RSD (%)	3.4	5.6	1.7	1.4	2.0	0.5	0.9
ABS	1.62	1.36	1.34	1.06	0.87	0.46	0.42
ABS	1.53	1.35	1.26	1.11	0.85	0.45	0.41
ABS	1.57	1.32	1.32	1.08	0.85	0.44	0.41
$\bar{X} \pm s$	1.57±0.045	1.34±0.021	1.31±0.042	1.08±0.025	0.86±0.012	0.45±0.01	0.41±0.006
RSD (%)	2.9	1.5	3.2	2.3	1.3	2.2	1.4
FRE	1.72	1.60	1.71	1.56	1.64	1.18	1.40
FRE	1.63	1.59	1.62	1.64	1.62	1.19	1.44
FRE	1.69	1.56	1.67	1.62	1.59	1.16	1.47
$\bar{X} \pm s$	1.68±0.046	1.58±0.021	1.67±0.045	1.61±0.042	1.62±0.025	1.18±0.015	1.44±0.035
RSD (%)	2.7	1.3	2.7	2.6	1.6	1.3	2.4
FRP	1.64	1.42	1.57	1.35	1.40	0.97	1.05
FRP	1.63	1.49	1.40	1.49	1.37	0.97	1.08
FRP	1.64	1.50	1.55	1.35	1.35	0.95	1.10
$\bar{X} \pm s$	1.64±0.006	1.47±0.044	1.51±0.093	1.40±0.081	1.37±0.025	0.96±0.012	1.08±0.025
RSD (%)	0.4	3.0	6.2	5.8	1.8	1.2	2.3

* $\bar{X}$ = mean; s = standard deviation; RSD = relative standard deviation.

TDCE

<i>Treatment</i>	<i>1 hr</i>	<i>8 hr</i>	<i>24 hr</i>	<i>72 hr</i>	<i>168 hr</i>	<i>500 hr</i>	<i>1000 hr</i>
Control	1.70	1.61	1.81	1.79	1.64	0.98	1.37
Control	1.62	1.63	1.88	1.76	1.59	0.99	1.39
Control	1.61	1.55	1.84	1.78	1.57	0.96	1.30
$\bar{X} \pm s$	1.64±0.049	1.60±0.042	1.84±0.035	1.78±0.015	1.60±0.036	0.98±0.015	1.35±0.047
RSD (%)	3.0	2.6	1.9	0.9	2.3	1.6	3.5
PVC	1.66	1.59	1.81	1.70	1.50	0.91	1.06
PVC	1.58	1.51	1.76	1.72	1.44	0.86	1.00
PVC	1.57	1.49	1.71	1.70	1.47	0.85	0.98
$\bar{X} \pm s$	1.60±0.049	1.53±0.053	1.76±0.05	1.71±0.012	1.47±0.03	0.87±0.032	1.01±0.042
RSD (%)	3.1	3.5	2.8	0.7	2.0	3.7	4.1
PTFE	1.64	1.51	1.64	1.43	1.18	0.65	0.79
PTFE	1.63	1.49	1.55	1.43	1.13	0.61	0.70
PTFE	1.51	1.37	1.59	1.41	1.14	0.66	0.71
$\bar{X} \pm s$	1.59±0.072	1.46±0.076	1.59±0.045	1.42±0.012	1.15±0.026	0.64±0.026	0.73±0.049
RSD (%)	4.5	5.2	2.8	0.8	2.3	4.1	6.7
FEP	1.67	1.54	1.59	1.49	1.24	0.69	0.78
FEP	1.59	1.50	1.60	1.51	1.24	0.70	0.77
FEP	1.52	1.35	1.63	1.47	1.20	0.68	0.75
$\bar{X} \pm s$	1.59±0.075	1.46±0.1	1.61±0.021	1.49±0.02	1.23±0.023	0.69±0.01	0.77±0.015
RSD (%)	4.7	6.8	1.3	1.3	1.9	1.4	2.0
ABS	1.48	1.21	1.23	0.89	0.64	0.28	0.27
ABS	1.44	1.20	1.15	0.94	0.62	0.27	0.26
ABS	1.47	1.16	1.20	0.91	0.62	0.26	0.26
$\bar{X} \pm s$	1.46±0.021	1.19±0.026	1.19±0.04	0.91±0.025	0.63±0.012	0.27±0.01	0.26±0.006
RSD (%)	1.4	2.2	3.4	2.8	1.8	3.7	2.2
FRE	1.66	1.53	1.75	1.57	1.52	0.95	1.15
FRE	1.56	1.51	1.66	1.63	1.48	0.95	1.20
FRE	1.61	1.47	1.69	1.61	1.46	0.92	1.21
$\bar{X} \pm s$	1.61±0.05	1.50±0.031	1.70±0.046	1.60±0.031	1.49±0.031	0.94±0.017	1.19±0.032
RSD (%)	3.1	2.0	2.7	1.9	2.1	1.8	2.7
FRP	1.56	1.30	1.51	1.25	1.21	0.75	0.80
FRP	1.54	1.36	1.35	1.39	1.18	0.74	0.84
FRP	1.54	1.37	1.49	1.25	1.15	0.72	0.82
$\bar{X} \pm s$	1.55±0.012	1.34±0.038	1.45±0.087	1.30±0.081	1.18±0.03	0.74±0.015	0.82±0.02
RSD (%)	0.7	2.8	6.0	6.2	2.5	2.1	2.4

• $\bar{X}$ = mean; s = standard deviation; RSD = relative standard deviation.

TCE

<i>Treatment</i>	<i>1 hr</i>	<i>8 hr</i>	<i>24 hr</i>	<i>72 hr</i>	<i>168 hr</i>	<i>500 hr</i>	<i>1000 hr</i>
Control	1.87	1.78	1.76	1.73	1.53	1.05	1.36
Control	1.79	1.80	1.82	1.71	1.49	1.06	1.37
Control	1.77	1.72	1.79	1.73	1.47	1.02	1.29
$\bar{X} \pm s$	1.81±0.053	1.77±0.042	1.79±0.03	1.72±0.012	1.50±0.031	1.04±0.021	1.34±0.044
RSD (%)	2.9	2.4	1.7	0.7	2.0	2.0	3.3
PVC	1.83	1.76	1.76	1.68	1.45	1.02	1.14
PVC	1.76	1.66	1.72	1.69	1.40	0.96	1.08
PVC	1.74	1.65	1.68	1.68	1.42	0.95	1.06
$\bar{X} \pm s$	1.78±0.047	1.69±0.061	1.72±0.04	1.68±0.006	1.42±0.025	0.98±0.038	1.09±0.042
RSD (%)	2.7	3.6	2.3	0.3	1.8	3.9	3.8
PTFE	1.80	1.63	1.53	1.26	1.00	0.55	0.55
PTFE	1.78	1.61	1.44	1.32	0.93	0.51	0.51
PTFE	1.65	1.49	1.49	1.29	0.95	0.55	0.52
$\bar{X} \pm s$	1.74±0.081	1.58±0.076	1.49±0.045	1.29±0.03	0.96±0.036	0.54±0.023	0.53±0.021
RSD (%)	4.7	4.8	3.0	2.3	3.8	4.3	4.0
FEP	1.82	1.65	1.47	1.33	1.03	0.60	0.60
FEP	1.74	1.61	1.47	1.36	1.04	0.61	0.59
FEP	1.66	1.45	1.50	1.32	1.00	0.59	0.58
$\bar{X} \pm s$	1.74±0.08	1.57±0.106	1.48±0.017	1.34±0.021	1.02±0.021	0.60±0.01	0.59±0.01
RSD (%)	4.6	6.7	1.2	1.6	2.0	1.7	1.7
ABS	1.58	1.11	0.86	0.53	0.33	0.14	0.12
ABS	1.51	1.09	0.83	0.56	0.32	0.14	0.12
ABS	1.53	1.07	0.85	0.55	0.31	0.13	0.11
$\bar{X} \pm s$	1.54±0.036	1.09±0.02	0.85±0.015	0.55±0.015	0.32±0.01	0.14±0.006	0.12±0.006
RSD (%)	2.3	1.8	1.8	2.8	3.1	4.2	4.9
FRE	1.84	1.70	1.72	1.54	1.44	1.01	1.15
FRE	1.73	1.67	1.63	1.61	1.41	1.01	1.20
FRE	1.78	1.63	1.67	1.58	1.38	0.98	1.19
$\bar{X} \pm s$	1.78±0.055	1.67±0.035	1.67±0.045	1.58±0.035	1.41±0.03	1.00±0.017	1.18±0.026
RSD (%)	3.1	2.1	2.7	2.2	2.1	1.7	2.2
FRP	1.73	1.45	1.45	1.14	1.02	0.63	0.61
FRP	1.70	1.51	1.30	1.28	0.99	0.63	0.63
FRP	1.71	1.52	1.41	1.13	0.96	0.62	0.63
$\bar{X} \pm s$	1.71±0.015	1.49±0.038	1.39±0.078	1.18±0.084	0.99±0.03	0.63±0.006	0.62±0.012
RSD (%)	0.9	2.5	5.6	7.1	3.0	0.9	1.9

* $\bar{X}$ = mean; s = standard deviation; RSD = relative standard deviation.

PCE

Treatment	1 hr	8 hr	24 hr	72 hr	168 hr	500 hr	1000 hr
Control	1.91	1.75	1.72	1.68	1.17	0.85	0.98
Control	1.80	1.80	1.77	1.64	1.12	0.87	1.01
Control	1.77	1.70	1.74	1.66	1.13	0.83	0.94
$\bar{X} \pm s$	1.83 $\pm$ 0.074	1.75 $\pm$ 0.05	1.74 $\pm$ 0.025	1.66 $\pm$ 0.02	1.14 $\pm$ 0.026	0.85 $\pm$ 0.02	0.98 $\pm$ 0.035
RSD (%)	4.0	2.9	1.4	1.2	2.3	2.4	3.6
PVC	1.85	1.73	1.69	1.59	1.10	0.84	0.80
PVC	1.76	1.61	1.64	1.58	1.02	0.80	0.74
PVC	1.76	1.63	1.60	1.56	1.07	0.76	0.72
$\bar{X} \pm s$	1.79 $\pm$ 0.052	1.66 $\pm$ 0.064	1.64 $\pm$ 0.045	1.58 $\pm$ 0.015	1.06 $\pm$ 0.04	0.80 $\pm$ 0.04	0.75 $\pm$ 0.042
RSD (%)	2.9	3.9	2.7	1.0	3.8	5.0	5.5
PTFE	1.74	1.43	1.17	0.75	0.43	0.21	0.15
PTFE	1.72	1.40	1.06	0.88	0.38	0.19	0.14
PTFE	1.57	1.29	1.15	0.84	0.41	0.20	0.15
$\bar{X} \pm s$	1.68 $\pm$ 0.093	1.37 $\pm$ 0.074	1.13 $\pm$ 0.059	0.82 $\pm$ 0.067	0.41 $\pm$ 0.025	0.20 $\pm$ 0.01	0.15 $\pm$ 0.006
RSD (%)	5.5	5.4	5.2	8.1	6.2	5.0	3.9
FEP	1.72	1.40	1.09	0.85	0.45	0.24	0.19
FEP	1.65	1.39	1.10	0.86	0.46	0.26	0.19
FEP	1.58	1.21	1.11	0.83	0.44	0.24	0.19
$\bar{X} \pm s$	1.65 $\pm$ 0.07	1.33 $\pm$ 0.107	1.10 $\pm$ 0.01	0.85 $\pm$ 0.015	0.45 $\pm$ 0.01	0.25 $\pm$ 0.012	0.19 $\pm$ 0
RSD (%)	4.2	8.0	0.9	1.8	2.2	4.7	0.0
ABS	1.41	0.79	0.42	0.20	0.095	0.044	0.028
ABS	1.46	0.77	0.42	0.21	0.081	0.045	0.026
ABS	1.44	0.76	0.43	0.21	0.078	0.040	0.049
$\bar{X} \pm s$	1.44 $\pm$ 0.025	0.77 $\pm$ 0.015	0.42 $\pm$ 0.006	0.21 $\pm$ 0.006	0.085 $\pm$ 0.009	0.043 $\pm$ 0.003	0.034 $\pm$ 0.013
RSD (%)	1.8	2.0	1.4	2.8	10.7	6.2	37.1
FRE	1.86	1.72	1.70	1.51	1.11	0.87	0.86
FRE	1.72	1.66	1.60	1.56	1.08	0.87	0.92
FRE	1.80	1.62	1.62	1.53	1.03	0.85	0.91
$\bar{X} \pm s$	1.79 $\pm$ 0.07	1.67 $\pm$ 0.05	1.64 $\pm$ 0.053	1.53 $\pm$ 0.025	1.09 $\pm$ 0.017	0.86 $\pm$ 0.012	0.90 $\pm$ 0.032
RSD (%)	3.9	3.0	3.2	1.6	1.6	1.3	3.6
FRP	1.75	1.42	1.39	1.06	0.73	0.47	0.35
FRP	1.71	1.49	1.25	1.21	0.72	0.48	0.35
FRP	1.72	1.52	1.35	1.06	0.68	0.47	0.36
$\bar{X} \pm s$	1.73 $\pm$ 0.021	1.48 $\pm$ 0.051	1.33 $\pm$ 0.072	1.11 $\pm$ 0.087	0.71 $\pm$ 0.026	0.47 $\pm$ 0.006	0.35 $\pm$ 0.006
RSD (%)	1.2	3.5	5.4	7.8	3.7	1.2	1.6

* $\bar{X}$ = mean; s = standard deviation; RSD = relative standard deviation.

BENZ

Treatment	1 hr	8 hr	24 hr	72 hr	168 hr	500 hr	1000 hr
Control	0.57	0.55	0.49	0.48	0.54	0.36	0.49
Control	0.54	0.54	0.51	0.47	0.53	0.37	0.50
Control	0.55	0.52	0.49	0.48	0.52	0.36	0.48
$\bar{X} \pm s$	0.55±0.015	0.54±0.015	0.50±0.012	0.48±0.006	0.53±0.01	0.36±0.006	0.49±0.01
RSD (%)	2.8	2.8	2.3	1.2	1.9	1.6	2.0
PVC	0.57	0.54	0.51	0.47	0.53	0.36	0.47
PVC	0.54	0.53	0.49	0.48	0.52	0.36	0.47
PVC	0.53	0.51	0.48	0.48	0.52	0.36	0.45
$\bar{X} \pm s$	0.55±0.021	0.53±0.015	0.49±0.015	0.48±0.006	0.52±0.006	0.36±0	0.46±0.012
RSD (%)	3.8	2.9	3.1	1.2	1.1	0.0	2.5
PTFE	0.56	0.53	0.48	0.44	0.49	0.31	0.38
PTFE	0.56	0.52	0.46	0.44	0.47	0.30	0.37
PTFE	0.52	0.49	0.47	0.44	0.46	0.31	0.38
$\bar{X} \pm s$	0.55±0.023	0.51±0.021	0.47±0.01	0.44±0	0.47±0.015	0.31±0.006	0.38±0.006
RSD (%)	4.2	4.1	2.1	0.0	3.2	1.9	1.5
FEP	0.57	0.55	0.46	0.45	0.49	0.31	0.38
FEP	0.55	0.52	0.47	0.46	0.48	0.32	0.39
FEP	0.53	0.48	0.47	0.44	0.46	0.31	0.38
$\bar{X} \pm s$	0.55±0.02	0.52±0.035	0.47±0.006	0.45±0.01	0.48±0.015	0.31±0.006	0.38±0.006
RSD (%)	3.6	6.8	1.2	2.2	3.2	1.8	1.5
ABS	0.51	0.42	0.34	0.26	0.23	0.10	0.10
ABS	0.49	0.42	0.33	0.27	0.22	0.10	0.093
ABS	0.50	0.41	0.34	0.26	0.22	0.10	0.090
$\bar{X} \pm s$	0.50±0.01	0.42±0.006	0.34±0.006	0.26±0.006	0.22±0.006	0.10±0	0.094±0.005
RSD (%)	2.0	1.4	1.7	2.2	2.6	0.0	5.4
FRE	0.57	0.52	0.48	0.45	0.52	0.35	0.44
FRE	0.53	0.52	0.46	0.47	0.52	0.35	0.47
FRE	0.55	0.50	0.47	0.46	0.51	0.35	0.46
$\bar{X} \pm s$	0.55±0.02	0.51±0.012	0.47±0.01	0.46±0.01	0.52±0.006	0.35±0	0.46±0.015
RSD (%)	3.6	2.2	2.1	2.2	1.1	0.0	3.3
FRP	0.54	0.49	0.46	0.40	0.48	0.30	0.36
FRP	0.53	0.50	0.42	0.44	0.47	0.31	0.36
FRP	0.55	0.50	0.46	0.40	0.45	0.30	0.37
$\bar{X} \pm s$	0.54±0.01	0.50±0.006	0.45±0.023	0.41±0.023	0.47±0.015	0.30±0.006	0.36±0.006
RSD (%)	1.9	1.2	5.2	5.6	3.3	1.9	1.6

* $\bar{X}$ = mean; s = standard deviation; RSD = relative standard deviation.

CLB

Treatment	1 hr	8 hr	24 hr	72 hr	168 hr	500 hr	1000 hr
Control	1.82	1.75	1.78	1.75	1.45	1.26	1.35
Control	1.75	1.77	1.82	1.74	1.42	1.26	1.36
Control	1.74	1.69	1.80	1.76	1.40	1.23	1.31
$\bar{X} \pm s$	1.77 $\pm$ 0.044	1.74 $\pm$ 0.042	1.80 $\pm$ 0.02	1.75 $\pm$ 0.01	1.42 $\pm$ 0.025	1.25 $\pm$ 0.017	1.34 $\pm$ 0.026
RSD (%)	2.5	2.4	1.1	0.6	1.8	1.4	2.0
PVC	1.80	1.74	1.77	1.69	1.37	1.20	1.18
PVC	1.72	1.66	1.73	1.71	1.34	1.14	1.14
PVC	1.70	1.64	1.71	1.70	1.35	1.14	1.13
$\bar{X} \pm s$	1.74 $\pm$ 0.053	1.68 $\pm$ 0.053	1.74 $\pm$ 0.031	1.70 $\pm$ 0.01	1.35 $\pm$ 0.015	1.16 $\pm$ 0.035	1.15 $\pm$ 0.026
RSD (%)	3.0	3.1	1.8	0.6	1.1	3.0	2.3
PTFE	1.77	1.64	1.63	1.41	1.10	0.80	0.69
PTFE	1.75	1.64	1.55	1.46	1.03	0.75	0.66
PTFE	1.65	1.51	1.59	1.44	1.06	0.79	0.67
$\bar{X} \pm s$	1.72 $\pm$ 0.064	1.60 $\pm$ 0.075	1.59 $\pm$ 0.04	1.44 $\pm$ 0.025	1.06 $\pm$ 0.035	0.78 $\pm$ 0.026	0.67 $\pm$ 0.015
RSD (%)	3.7	4.7	2.5	1.8	3.3	3.4	2.3
FEP	1.79	1.67	1.58	1.45	1.11	0.83	0.73
FEP	1.73	1.63	1.56	1.48	1.10	0.85	0.74
FEP	1.68	1.50	1.60	1.45	1.08	0.83	0.74
$\bar{X} \pm s$	1.73 $\pm$ 0.055	1.60 $\pm$ 0.089	1.58 $\pm$ 0.02	1.46 $\pm$ 0.017	1.10 $\pm$ 0.015	0.84 $\pm$ 0.012	0.74 $\pm$ 0.006
RSD (%)	3.2	5.6	1.3	1.2	1.4	1.4	0.8
ABS	1.60	0.94	0.62	0.34	0.18	0.089	0.068
ABS	1.44	0.92	0.61	0.35	0.17	0.085	0.061
ABS	1.47	0.92	0.63	0.34	0.17	0.083	0.066
$\bar{X} \pm s$	1.50 $\pm$ 0.085	0.93 $\pm$ 0.012	0.62 $\pm$ 0.01	0.34 $\pm$ 0.006	0.17 $\pm$ 0.006	0.086 $\pm$ 0.003	0.065 $\pm$ 0.004
RSD (%)	5.7	1.2	1.6	1.7	3.3	3.6	5.5
FRE	1.80	1.69	1.75	1.58	1.38	1.19	1.17
FRE	1.71	1.67	1.64	1.66	1.35	1.19	1.21
FRE	1.76	1.64	1.71	1.62	1.33	1.17	1.21
$\bar{X} \pm s$	1.76 $\pm$ 0.045	1.67 $\pm$ 0.025	1.70 $\pm$ 0.056	1.62 $\pm$ 0.04	1.35 $\pm$ 0.025	1.18 $\pm$ 0.012	1.20 $\pm$ 0.023
RSD (%)	2.6	1.5	3.3	2.5	1.9	1.0	1.9
FRP	1.70	1.48	1.52	1.22	1.00	0.72	0.55
FRP	1.69	1.54	1.37	1.36	0.97	0.72	0.56
FRP	1.71	1.56	1.49	1.21	0.95	0.72	0.59
$\bar{X} \pm s$	1.70 $\pm$ 0.01	1.53 $\pm$ 0.042	1.46 $\pm$ 0.079	1.26 $\pm$ 0.084	0.97 $\pm$ 0.025	0.72 $\pm$ 0	0.57 $\pm$ 0.021
RSD (%)	0.6	2.7	5.4	6.6	2.6	0.0	3.7

* $\bar{X}$ = mean; s = standard deviation; RSD = relative standard deviation.

ODCB

Treatment	1 hr	8 hr	24 hr	72 hr	168 hr	500 hr	1000 hr
Control	1.84	1.76	1.80	1.78	1.33	1.36	1.25
Control	1.77	1.78	1.82	1.76	1.31	1.37	1.27
Control	1.76	1.71	1.81	1.77	1.30	1.33	1.23
$\bar{X} \pm s$	1.79±0.044	1.75±0.036	1.81±0.01	1.77±0.01	1.31±0.015	1.35±0.021	1.25±0.02
RSD (%)	2.4	2.1	0.6	0.6	1.2	1.5	1.6
PVC	1.82	1.74	1.76	1.69	1.26	1.28	1.09
PVC	1.73	1.66	1.73	1.70	1.23	1.24	1.07
PVC	1.71	1.66	1.73	1.70	1.23	1.23	1.06
$\bar{X} \pm s$	1.75±0.059	1.69±0.046	1.74±0.017	1.70±0.006	1.24±0.017	1.25±0.026	1.07±0.015
RSD (%)	3.3	2.7	1.0	0.3	1.4	2.1	1.4
PTFE	1.77	1.63	1.59	1.34	0.95	0.76	0.52
PTFE	1.76	1.63	1.52	1.42	0.88	0.70	0.51
PTFE	1.66	1.51	1.57	1.38	0.91	0.74	0.54
$\bar{X} \pm s$	1.73±0.061	1.59±0.069	1.56±0.036	1.38±0.04	0.91±0.035	0.73±0.031	0.52±0.015
RSD (%)	3.5	4.4	2.3	2.9	3.8	4.2	2.9
FEP	1.79	1.64	1.54	1.37	0.93	0.78	0.59
FEP	1.74	1.62	1.52	1.40	0.93	0.80	0.57
FEP	1.72	1.49	1.55	1.37	0.91	0.79	0.58
$\bar{X} \pm s$	1.75±0.036	1.58±0.081	1.54±0.015	1.38±0.017	0.92±0.012	0.79±0.01	0.58±0.01
RSD (%)	2.1	5.1	1.0	1.3	1.3	1.3	1.7
ABS	1.56	0.72	0.33	0.13	0.053	0.032	0.022
ABS	1.40	0.71	0.33	0.13	0.055	0.030	0.022
ABS	1.41	0.71	0.34	0.14	0.052	0.029	0.020
$\bar{X} \pm s$	1.46±0.09	0.71±0.006	0.33±0.006	0.13±0.006	0.053±0.002	0.030±0.002	0.021±0.001
RSD (%)	6.2	0.8	1.7	4.3	2.9	5.0	5.4
FRE	1.81	1.71	1.76	1.59	1.26	1.26	1.06
FRE	1.72	1.69	1.65	1.67	1.24	1.26	1.11
FRE	1.78	1.68	1.72	1.63	1.23	1.24	1.12
$\bar{X} \pm s$	1.77±0.046	1.69±0.015	1.71±0.056	1.63±0.04	1.24±0.015	1.25±0.012	1.10±0.032
RSD (%)	2.6	0.9	3.3	2.5	1.2	0.9	2.9
FRP	1.70	1.47	1.46	1.14	0.81	0.61	0.36
FRP	1.69	1.53	1.34	1.28	0.79	0.63	0.37
FRP	1.72	1.57	1.44	1.14	0.77	0.63	0.40
$\bar{X} \pm s$	1.70±0.015	1.52±0.05	1.41±0.064	1.19±0.081	0.79±0.02	0.62±0.012	0.38±0.021
RSD (%)	0.9	3.3	4.5	6.8	2.5	1.9	5.5

* $\bar{X}$ = mean; s = standard deviation; RSD = relative standard deviation.

PDCB

Treatment	1 hr	8 hr	24 hr	72 hr	168 hr	500 hr	1000 hr
Control	1.81	1.67	1.71	1.70	1.26	1.16	1.11
Control	1.73	1.71	1.73	1.66	1.23	1.16	1.12
Control	1.71	1.63	1.71	1.67	1.24	1.13	1.08
$\bar{X} \pm s$	1.75 $\pm$ 0.053	1.67 $\pm$ 0.04	1.72 $\pm$ 0.012	1.68 $\pm$ 0.021	1.24 $\pm$ 0.015	1.15 $\pm$ 0.017	1.10 $\pm$ 0.021
RSD (%)	3.0	2.4	0.7	1.2	1.2	1.5	1.9
PVC	1.78	1.65	1.55	1.58	1.14	1.06	0.86
PVC	1.69	1.56	1.61	1.58	1.11	1.00	0.81
PVC	1.69	1.55	1.61	1.59	1.13	1.00	0.80
$\bar{X} \pm s$	1.72 $\pm$ 0.052	1.59 $\pm$ 0.055	1.63 $\pm$ 0.029	1.58 $\pm$ 0.006	1.13 $\pm$ 0.015	1.02 $\pm$ 0.035	0.82 $\pm$ 0.032
RSD (%)	3.0	3.5	1.8	0.4	1.4	3.4	3.9
PTFE	1.70	1.46	1.35	1.02	0.66	0.44	0.28
PTFE	1.70	1.45	1.25	1.12	0.60	0.40	0.28
PTFE	1.57	1.35	1.33	1.09	0.63	0.44	0.31
$\bar{X} \pm s$	1.66 $\pm$ 0.075	1.42 $\pm$ 0.061	1.31 $\pm$ 0.053	1.08 $\pm$ 0.051	0.63 $\pm$ 0.03	0.43 $\pm$ 0.023	0.29 $\pm$ 0.017
RSD (%)	4.5	4.3	4.0	4.8	4.8	5.4	6.0
FEP	1.72	1.45	1.29	1.11	0.68	0.49	0.35
FEP	1.65	1.47	1.28	1.13	0.68	0.49	0.32
FEP	1.63	1.30	1.30	1.09	0.67	0.49	0.33
$\bar{X} \pm s$	1.67 $\pm$ 0.047	1.41 $\pm$ 0.093	1.29 $\pm$ 0.01	1.11 $\pm$ 0.02	0.68 $\pm$ 0.006	0.49 $\pm$ 0	0.33 $\pm$ 0.015
RSD (%)	2.8	6.6	0.8	1.8	0.9	0.0	4.6
ABS	1.46	0.62	0.27	0.13	0.046	0.027	0.012
ABS	1.35	0.60	0.26	0.11	0.049	0.032	0.018
ABS	1.36	0.61	0.27	0.13	0.044	0.027	0.026
$\bar{X} \pm s$	1.39 $\pm$ 0.061	0.61 $\pm$ 0.01	0.27 $\pm$ 0.006	0.12 $\pm$ 0.012	0.046 $\pm$ 0.003	0.029 $\pm$ 0.003	0.019 $\pm$ 0.007
RSD (%)	4.4	1.6	2.2	9.4	5.4	10.1	37.6
FRE	1.77	1.63	1.65	1.47	1.14	1.05	0.87
FRE	1.66	1.60	1.53	1.54	1.11	1.05	0.91
FRE	1.74	1.58	1.60	1.51	1.09	1.03	0.92
$\bar{X} \pm s$	1.72 $\pm$ 0.057	1.60 $\pm$ 0.025	1.59 $\pm$ 0.06	1.51 $\pm$ 0.035	1.11 $\pm$ 0.025	1.04 $\pm$ 0.012	0.90 $\pm$ 0.026
RSD (%)	3.3	1.6	3.8	2.3	2.3	1.1	2.9
FRP	1.64	1.31	1.22	0.90	0.59	0.39	0.21
FRP	1.62	1.36	1.13	1.03	0.57	0.42	0.21
FRP	1.64	1.41	1.20	0.90	0.56	0.41	0.24
$\bar{X} \pm s$	1.63 $\pm$ 0.012	1.36 $\pm$ 0.05	1.18 $\pm$ 0.047	0.94 $\pm$ 0.075	0.57 $\pm$ 0.015	0.41 $\pm$ 0.015	0.22 $\pm$ 0.017
RSD (%)	0.7	3.7	4.0	8.0	2.7	3.8	7.9

* $\bar{X}$ = mean; s = standard deviation; RSD = relative standard deviation.

OXYL

Treatment	1 hr	8 hr	24 hr	72 hr	168 hr	500 hr	1000 hr
Control	1.39	1.32	1.44	1.42	0.94	0.95	0.88
Control	1.33	1.32	1.46	1.40	0.93	0.96	0.89
Control	1.33	1.28	1.44	1.41	0.92	0.93	0.86
$\bar{X} \pm s$	1.35 $\pm$ 0.035	1.31 $\pm$ 0.023	1.45 $\pm$ 0.012	1.41 $\pm$ 0.01	0.93 $\pm$ 0.01	0.95 $\pm$ 0.015	0.88 $\pm$ 0.015
RSD (%)	2.6	1.8	0.8	0.7	1.1	1.6	1.7
PVC	1.38	1.31	1.43	1.39	0.91	0.93	0.83
PVC	1.31	1.25	1.40	1.39	0.89	0.91	0.82
PVC	1.30	1.24	1.39	1.39	0.90	0.91	0.80
$\bar{X} \pm s$	1.33 $\pm$ 0.044	1.27 $\pm$ 0.038	1.41 $\pm$ 0.021	1.39 $\pm$ 0	0.90 $\pm$ 0.01	0.92 $\pm$ 0.012	0.82 $\pm$ 0.015
RSD (%)	3.3	3.0	1.5	0.0	1.1	1.3	1.9
PTFE	1.35	1.24	1.32	1.17	0.74	0.62	0.45
PTFE	1.33	1.24	1.26	1.20	0.69	0.58	0.45
PTFE	1.26	1.14	1.30	1.17	0.71	0.61	0.47
$\bar{X} \pm s$	1.31 $\pm$ 0.047	1.21 $\pm$ 0.058	1.29 $\pm$ 0.031	1.18 $\pm$ 0.017	0.71 $\pm$ 0.025	0.60 $\pm$ 0.021	0.46 $\pm$ 0.012
RSD (%)	3.6	4.8	2.4	1.5	3.5	3.5	2.5
FEP	1.37	1.26	1.27	1.18	0.73	0.63	0.49
FEP	1.32	1.24	1.27	1.20	0.72	0.64	0.48
FEP	1.27	1.13	1.27	1.18	0.70	0.63	0.49
$\bar{X} \pm s$	1.32 $\pm$ 0.05	1.21 $\pm$ 0.07	1.27 $\pm$ 0	1.19 $\pm$ 0.012	0.72 $\pm$ 0.015	0.63 $\pm$ 0.006	0.49 $\pm$ 0.006
RSD (%)	3.8	5.8	0.0	1.0	2.1	0.9	1.2
ABS	1.19	0.72	0.47	0.23	0.086	0.049	0.031
ABS	1.12	0.70	0.47	0.23	0.085	0.051	0.036
ABS	1.13	0.70	0.48	0.24	0.084	0.047	0.035
$\bar{X} \pm s$	1.15 $\pm$ 0.038	0.71 $\pm$ 0.012	0.47 $\pm$ 0.006	0.23 $\pm$ 0.006	0.085 $\pm$ 0.001	0.049 $\pm$ 0.002	0.034 $\pm$ 0.003
RSD (%)	3.3	1.6	1.2	2.5	1.2	4.1	7.8
FRE	1.38	1.27	1.43	1.30	0.93	0.92	0.80
FRE	1.30	1.26	1.34	1.37	0.91	0.93	0.84
FRE	1.33	1.25	1.39	1.34	0.89	0.91	0.84
$\bar{X} \pm s$	1.34 $\pm$ 0.04	1.26 $\pm$ 0.01	1.39 $\pm$ 0.045	1.34 $\pm$ 0.035	0.91 $\pm$ 0.02	0.92 $\pm$ 0.01	0.83 $\pm$ 0.023
RSD (%)	3.0	0.8	3.3	2.6	2.2	1.1	2.8
FRP	1.32	1.16	1.30	1.12	0.77	0.68	0.48
FRP	1.31	1.20	1.19	1.24	0.75	0.70	0.49
FRP	1.32	1.22	1.30	1.14	0.73	0.69	0.51
$\bar{X} \pm s$	1.32 $\pm$ 0.006	1.19 $\pm$ 0.031	1.26 $\pm$ 0.064	1.17 $\pm$ 0.064	0.75 $\pm$ 0.02	0.69 $\pm$ 0.01	0.49 $\pm$ 0.015
RSD (%)	0.4	2.6	5.0	5.5	2.7	1.4	3.1

* $\bar{X}$ = mean; s = standard deviation; RSD = relative standard deviation.

MXYL

<i>Treatment</i>	<i>1 hr</i>	<i>8 hr</i>	<i>24 hr</i>	<i>72 hr</i>	<i>168 hr</i>	<i>500 hr</i>	<i>1000 hr</i>
Control	1.48	1.38	1.49	1.47	0.86	0.89	0.79
Control	1.41	1.39	1.51	1.44	0.85	0.90	0.80
Control	1.40	1.34	1.48	1.46	0.84	0.87	0.77
$\bar{X} \pm s$	1.43 $\pm$ 0.044	1.37 $\pm$ 0.026	1.49 $\pm$ 0.015	1.46 $\pm$ 0.015	0.85 $\pm$ 0.01	0.89 $\pm$ 0.015	0.79 $\pm$ 0.015
RSD (%)	3.0	1.9	1.0	1.0	1.2	1.7	1.9
PVC	1.46	1.37	1.47	1.42	0.82	0.87	0.70
PVC	1.38	1.29	1.43	1.43	0.80	0.84	0.68
PVC	1.38	1.29	1.42	1.42	0.82	0.83	0.67
$\bar{X} \pm s$	1.41 $\pm$ 0.046	1.32 $\pm$ 0.046	1.44 $\pm$ 0.026	1.42 $\pm$ 0.006	0.81 $\pm$ 0.012	0.85 $\pm$ 0.021	0.68 $\pm$ 0.015
RSD (%)	3.3	3.5	1.8	0.4	1.4	2.5	2.2
PTFE	1.41	1.26	1.28	1.04	0.57	0.44	0.27
PTFE	1.40	1.25	1.20	1.11	0.51	0.40	0.27
PTFE	1.30	1.15	1.25	1.08	0.54	0.43	0.29
$\bar{X} \pm s$	1.37 $\pm$ 0.061	1.22 $\pm$ 0.061	1.24 $\pm$ 0.04	1.08 $\pm$ 0.035	0.54 $\pm$ 0.03	0.42 $\pm$ 0.021	0.28 $\pm$ 0.012
RSD (%)	4.4	5.0	3.3	3.3	5.6	4.9	4.2
FEP	1.44	1.27	1.22	1.10	0.57	0.48	0.34
FEP	1.37	1.25	1.22	1.11	0.57	0.48	0.32
FEP	1.32	1.13	1.23	1.09	0.55	0.48	0.32
$\bar{X} \pm s$	1.38 $\pm$ 0.06	1.22 $\pm$ 0.076	1.22 $\pm$ 0.006	1.10 $\pm$ 0.01	0.56 $\pm$ 0.012	0.48 $\pm$ 0	0.33 $\pm$ 0.012
RSD (%)	4.4	6.2	0.5	0.9	2.0	0.0	3.5
ABS	1.22	0.68	0.40	0.18	0.068	0.050	0.033
ABS	1.16	0.66	0.40	0.18	0.068	0.056	0.030
ABS	1.17	0.66	0.41	0.18	0.063	0.046	0.046
$\bar{X} \pm s$	1.18 $\pm$ 0.032	0.67 $\pm$ 0.012	0.40 $\pm$ 0.006	0.18 $\pm$ 0	0.066 $\pm$ 0.003	0.051 $\pm$ 0.005	0.036 $\pm$ 0.009
RSD (%)	2.7	1.7	1.4	0.0	4.4	9.9	23.4
FRE	1.46	1.34	1.47	1.33	0.84	0.87	0.71
FRE	1.37	1.32	1.38	1.40	0.82	0.87	0.74
FRE	1.41	1.30	1.42	1.37	0.80	0.86	0.74
$\bar{X} \pm s$	1.41 $\pm$ 0.045	1.32 $\pm$ 0.02	1.42 $\pm$ 0.045	1.37 $\pm$ 0.035	0.82 $\pm$ 0.02	0.87 $\pm$ 0.006	0.73 $\pm$ 0.017
RSD (%)	3.2	1.5	3.2	2.6	2.4	0.7	2.4
FRP	1.39	1.19	1.28	1.07	0.64	0.55	0.35
FRP	1.38	1.23	1.18	1.19	0.62	0.57	0.34
FRP	1.38	1.24	1.27	1.08	0.60	0.56	0.36
$\bar{X} \pm s$	1.38 $\pm$ 0.006	1.22 $\pm$ 0.026	1.24 $\pm$ 0.055	1.11 $\pm$ 0.067	0.62 $\pm$ 0.02	0.56 $\pm$ 0.01	0.35 $\pm$ 0.01
RSD (%)	0.4	2.2	4.4	6.0	3.2	1.8	2.9

* $\bar{X}$ = mean; s = standard deviation; RSD = relative standard deviation.

MNT

<i>Treatment</i>	<i>1 hr</i>	<i>8 hr</i>	<i>24 hr</i>	<i>72 hr</i>	<i>168 hr</i>	<i>500 hr</i>	<i>1000 hr</i>
Control	1.89	1.89	1.92	1.93	1.47	1.80	1.43
Control	1.91	1.92	1.95	1.94	1.45	1.81	1.42
Control	1.91	1.88	1.97	1.94	1.45	1.80	1.41
$\bar{X} \pm s$	1.90 $\pm$ 0.012	1.90 $\pm$ 0.021	1.95 $\pm$ 0.025	1.94 $\pm$ 0.006	1.46 $\pm$ 0.012	1.80 $\pm$ 0.006	1.42 $\pm$ 0.01
RSD (%)	0.6	1.1	1.3	0.3	0.8	0.3	0.7
PVC	1.91	1.90	1.94	1.92	1.45	1.78	1.39
PVC	1.90	1.89	1.94	1.94	1.44	1.74	1.37
PVC	1.87	1.87	1.92	1.93	1.44	1.77	1.38
$\bar{X} \pm s$	1.89 $\pm$ 0.021	1.89 $\pm$ 0.015	1.93 $\pm$ 0.012	1.93 $\pm$ 0.01	1.44 $\pm$ 0.006	1.76 $\pm$ 0.021	1.38 $\pm$ 0.01
RSD (%)	1.1	0.8	0.6	0.5	0.4	1.2	0.7
PTFE	1.90	1.88	1.93	1.89	1.43	1.69	1.29
PTFE	1.90	1.89	1.91	1.90	1.38	1.68	1.27
PTFE	1.89	1.88	1.91	1.91	1.38	1.69	1.29
$\bar{X} \pm s$	1.90 $\pm$ 0.006	1.88 $\pm$ 0.006	1.92 $\pm$ 0.012	1.90 $\pm$ 0.01	1.40 $\pm$ 0.029	1.69 $\pm$ 0.006	1.28 $\pm$ 0.012
RSD (%)	0.3	0.3	0.6	0.5	2.1	0.3	0.9
FEP	1.92	1.88	1.89	1.89	1.43	1.68	1.28
FEP	1.90	1.88	1.92	1.90	1.39	1.70	1.29
FEP	1.90	1.88	1.94	1.89	1.38	1.70	1.29
$\bar{X} \pm s$	1.91 $\pm$ 0.012	1.88 $\pm$ 0	1.92 $\pm$ 0.025	1.89 $\pm$ 0.006	1.40 $\pm$ 0.026	1.69 $\pm$ 0.012	1.29 $\pm$ 0.006
RSD (%)	0.6	0.0	1.3	0.3	1.9	0.7	0.4
ABS	1.88	1.34	1.00	0.61	0.29	0.20	0.11
ABS	1.68	1.33	1.00	0.63	0.28	0.19	0.10
ABS	1.72	1.35	1.03	0.62	0.28	0.19	0.10
$\bar{X} \pm s$	1.76 $\pm$ 0.106	1.34 $\pm$ 0.01	1.01 $\pm$ 0.017	0.62 $\pm$ 0.01	0.28 $\pm$ 0.006	0.19 $\pm$ 0.006	0.10 $\pm$ 0.006
RSD (%)	6.0	0.7	1.7	1.6	2.0	3.0	5.6
FRE	1.91	1.89	1.91	1.90	1.38	1.74	1.35
FRE	1.88	1.89	1.91	1.90	1.42	1.75	1.35
FRE	1.89	1.88	1.91	1.89	1.39	1.73	1.35
$\bar{X} \pm s$	1.89 $\pm$ 0.015	1.89 $\pm$ 0.006	1.91 $\pm$ 0	1.90 $\pm$ 0.006	1.40 $\pm$ 0.021	1.74 $\pm$ 0.01	1.35 $\pm$ 0
RSD (%)	0.8	0.3	0.0	0.3	1.5	0.6	0.0
FRP	1.87	1.81	1.83	1.73	1.26	1.36	0.90
FRP	1.88	1.83	1.80	1.76	1.23	1.37	0.89
FRP	1.88	1.86	1.83	1.71	1.22	1.38	0.92
$\bar{X} \pm s$	1.88 $\pm$ 0.006	1.83 $\pm$ 0.025	1.82 $\pm$ 0.017	1.73 $\pm$ 0.025	1.24 $\pm$ 0.021	1.37 $\pm$ 0.01	0.90 $\pm$ 0.015
RSD (%)	0.3	1.4	1.0	1.5	1.7	0.7	1.7

* $\bar{X}$ = mean; s = standard deviation; RSD = relative standard deviation.

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words) The first part of this report contains the results of a literature review on whether four polymeric materials [acrylonitrile butadiene styrene (ABS), fluorinated ethylene propylene (FEP), fiberglass-reinforced epoxy (FRE) and fiberglass-reinforced plastic (FRP)] should be used in well casings when monitoring groundwater. The second part of this report contains the results of a laboratory study that compares sorption of low (mg/L) levels of dissolved organics by these four materials with sorption by two commonly used polymeric well casing materials [polyvinyl chloride (PVC) and polytetrafluoroethylene (PTFE)]. During the six-week laboratory study, ABS sorbed analytes much more rapidly and to a greater extent than the other materials, and PVC and FRE sorbed analytes the most slowly and to the least extent of the materials tested. As the study progressed there were an increasing number of unidentified peaks in the HPLC chromatograms of some of the samples. By the end of the study (1000 hours), there were 11 additional peaks in the ABS samples, 5 in the FRP samples and 1 in the FRE samples. Analysis by purge-and-trap GC/MS of the 1000-hour samples and 500-hour samples from a leaching study revealed the identity of some of these peaks.					
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