

**Prepared in cooperation with the  
U.S. Air Force**

**Radiochemical Sampling and Analysis of  
Shallow Ground Water and Sediment at the  
BOMARC Missile Facility, East-Central  
New Jersey, 1999–2000**

Scientific Investigations Report 2005-5062

**U.S. Department of the Interior  
U.S. Geological Survey**

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By Zoltan Szabo, Otto S. Zapecza, Jeannette H. Oden, and Donald E. Rice

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**U.S. Department of the Interior  
U.S. Geological Survey**

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## Conversion Factors, Vertical Datum, and Abbreviated Water-Quality Units

Multiply	By	To obtain
<b>Length</b>		
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
<b>Area</b>		
square mile (mi <sup>2</sup> )	2.590	square kilometer (km <sup>2</sup> )
<b>Volume</b>		
ounce, fluid (fl. oz)	29.57	milliliter
ounce, fluid (fl. oz)	0.02957	liter (L)
gallon (gal)	3.785	liter (L)
<b>Flow rate</b>		
foot per day (ft/d)	0.3048	meter per day (m/d)
<b>Mass</b>		
ounce, avoirdupois (oz)	28.35	gram
ounce, avoirdupois (oz)	28,349	milligram
ounce, avoirdupois (oz)	28,349,000	microgram

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 29).

Horizontal coordinate information is referenced either to the North American Datum of 1983 (NAD 83) or North American Datum of 1927 (NAD 27).

Water-quality abbreviations:

nm	nanometer
μm	micrometer
ng/L	nanograms per liter
μg/L	micrograms per liter
mg/L	milligrams per liter
μg/kg	micrograms per kilogram
μg/g	micrograms per gram
pCi	picocurie
pCi/L	picocurie per liter
pCi/g	picocurie per gram
HCl	hydrochloric acid
pCi/μg	picocurie per microgram
mg/m <sup>3</sup>	milligrams per cubic meter
DIW	deionized water
<	less than
>	greater
≤	less than or equal to
≥	greater than or equal to
SSMDC	sample specific minimum detectable concentration
PE	precision estimate
M	Molar, or moles
μM	micromolar
Am	americum
Cs	cesium
Pu	plutonium
Th	thorium
U	uranium
Ra	radium
KeV	kiloelectron volts
MeV	million electron volts
LRL	laboratory reporting limit
HNO <sub>3</sub>	nitric acid

# Radiochemical Sampling and Analysis of Shallow Ground Water and Sediment at the BOMARC Missile Facility, East-Central New Jersey, 1999–2000

By Zoltan Szabo, Otto S. Zapecza, Jeannette H. Oden, and Donald E. Rice

## Abstract

A field sampling experiment was designed using low-flow purging with a portable pump and sample-collection equipment for the collection of water and sediment samples from observation wells screened in the Kirkwood-Cohansey aquifer system to determine radionuclide or trace-element concentrations for various size fractions. Selected chemical and physical characteristics were determined for water samples from observation wells that had not been purged for years. The sampling was designed to define any particulate, colloidal, and solution-phase associations of radionuclides or trace elements in ground water by means of filtration and ultrafiltration techniques. Turbidity was monitored and allowed to stabilize before samples were collected by means of the low-flow purging technique rather than by the traditional method of purging a fixed volume of water at high-flow rates from the observation well. A minimum of four water samples was collected from each observation well. The samples of water from each well were collected in the following sequence. (1) A raw unfiltered sample was collected within the first minutes of pumping. (2) A raw unfiltered sample was collected after at least three casing volumes of water were removed and turbidity stabilized. (3) A sample was collected after the water was filtered with a 0.45-micron filter. (4) A sample was collected after the water passed through a 0.45-micron filter and a 0.003-micron tangential-flow ultrafilter in sequence. In some cases, a fifth sample was collected after the water passed through a 0.45-micron filter and a 0.05-micron filter in sequence to test for colloids of 0.003 microns to 0.05 microns in size. The samples were analyzed for the concentration of manmade radionuclides plutonium-238 and -239 plus -240, and americium-241. The samples also were analyzed for concentrations of uranium-234, -235, and -238 to determine whether uranium-234 isotope enrichment (resulting from industrial processing) is present. A subset of samples was analyzed for concentrations of thorium-232, -230, and -228 to determine if thorium-228 isotope enrichment, also likely to result from industrial processing, is present.

Concentrations of plutonium isotopes and americium-241 in the water samples were less than 0.1 picocurie per liter, the laboratory reporting level for these manmade radionuclides,

with the exception of one americium-241 concentration from a filtered sample. A sequential split sample from the same well did not contain a detectable concentration of americium-241, however. Other filtered and unfiltered samples of water from the same well did not contain quantities of americium-241 nearly as high as 0.1 pCi/L. Therefore, the presence of americium-241 in a quantifiable concentration in water samples from this well could not be confirmed. Neither plutonium nor americium was detected in samples of settled sediment collected from the bottom of the wells. Concentrations of uranium isotopes (maximum of 0.05 and 0.08 picocuries per liter of uranium-238 and uranium-234, respectively) were measurable in unfiltered samples of turbid water from one well and in the settled bottom sediment from 6 wells (maximum concentrations of 0.25 and 0.20 picocuries per gram of uranium-238 and uranium-234, respectively). The uranium-234/uranium-238 isotopic ratio was near 1:1, which indicates natural uranium. The analytical results, therefore, indicate that no manmade radionuclide contamination is present in any of the well-bottom sediments, or unfiltered or filtered water samples from any of the sampled wells. No evidence of manmade radionuclide contamination was observed in the aquifer as settled or suspended particulates, colloids, or in the dissolved phase.

## Introduction

A fire at the BOMARC (Boeing Michigan Aeronautical Research Center) Missile Facility, hereafter called the Facility, in June 1960 caused the release of a small amount of plutonium (Pu) to the environment. The Facility is located in Plumstead Township in Ocean County in east-central New Jersey in the Pine Barrens Preserve and is underlain by the sediments that compose the Kirkwood-Cohansey aquifer system (fig. 1). The aquifer system is the sole source of drinking water in the area. The fire at the Facility occurred in missile-launch Shelter 204 (fig. 2). A missile and its nuclear warhead were partially consumed in the fire. An estimated 300 grams of Pu was flushed from the site during fire-fighting activities. Most of the Pu was recovered during cleanup and restoration activities. Local contamination of shallow soil by radioactivity has been

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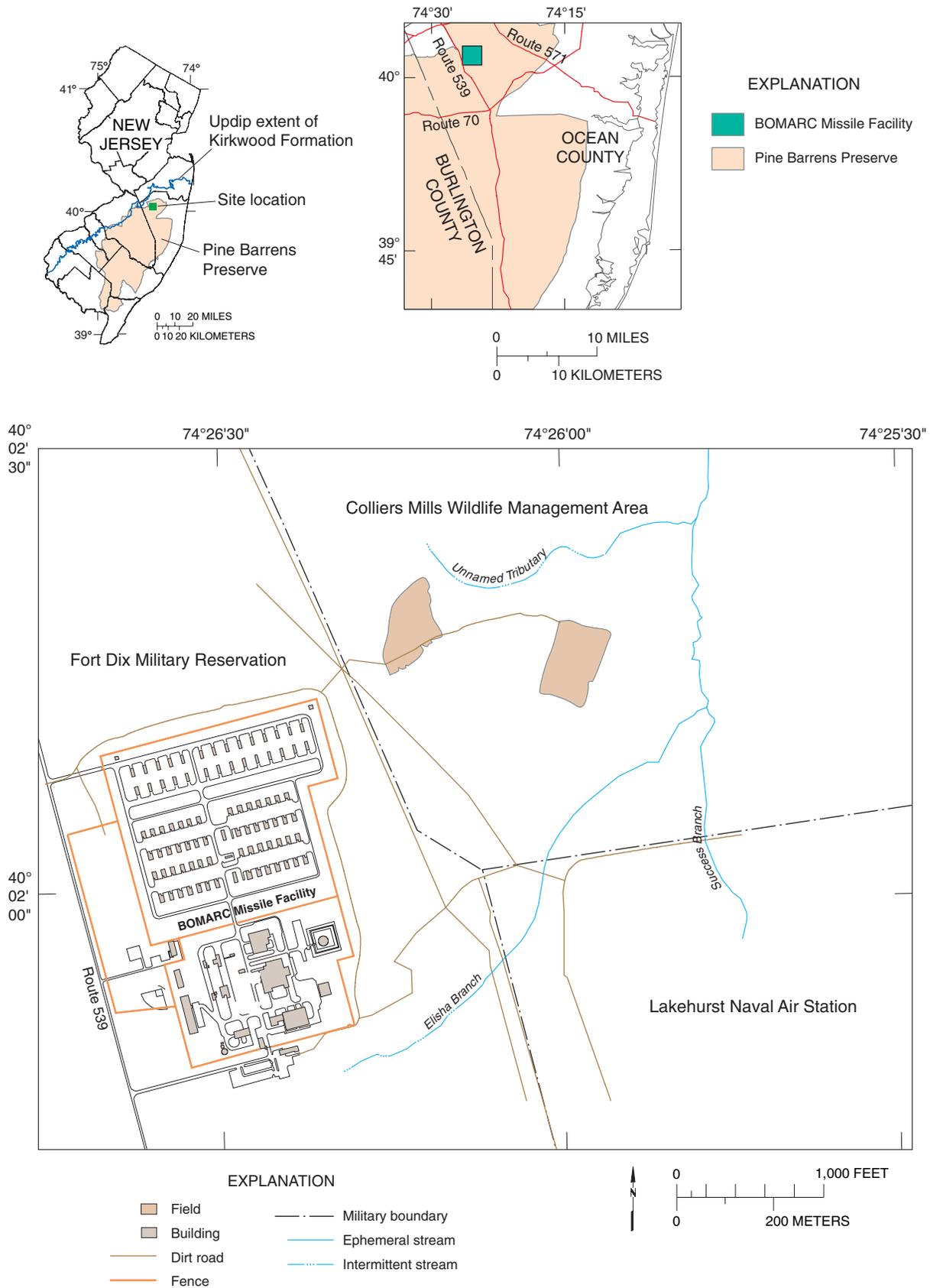
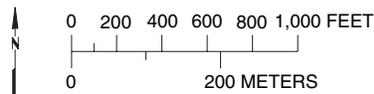
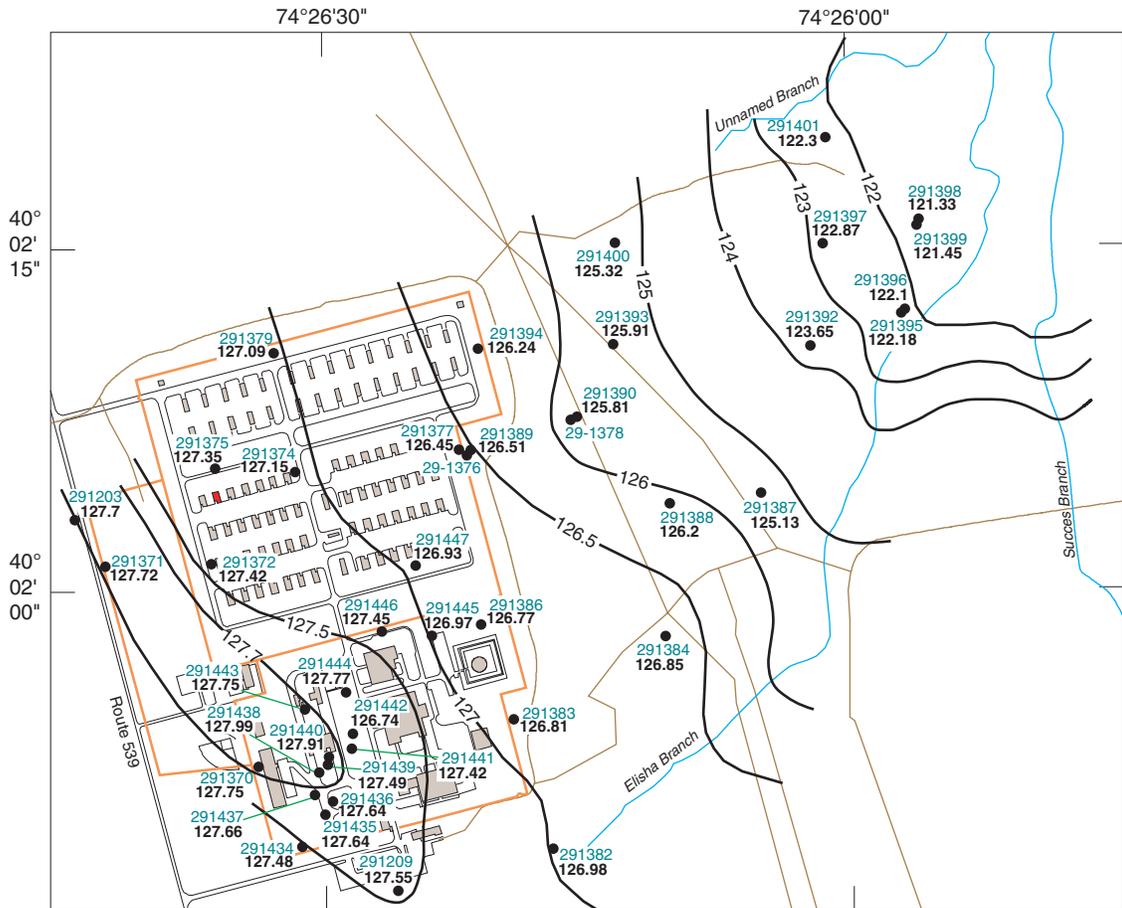


Figure 1. Location of BOMARC Missile Facility, Ocean County, New Jersey.



EXPLANATION

- Building
- Shelter 204
- 126 POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval (in feet) is variable. Datum is NGVD of 1929
- Dirt road
- Fence
- 291443 ● OBSERVATION WELL--Upper number is well number and lower number is altitude of water level, in feet. Datum is NGVD of 1929

**Figure 2.** The potentiometric surface, Kirkwood-Cohansey aquifer system, BOMARC Missile Facility, Ocean County, New Jersey, March 30, 2000.

#### 4 Radiochemical Sampling and Analysis of Shallow Ground Water and Sediment at the BOMARC Missile Facility, N.J.

documented in the vicinity of missile Shelter 204, however (Earth Technology Corporation, 1991). Plutonium and americium (Am) are strongly adsorbed to, and are retained on, soil particles (Krey, 1976; Hulse and others, 1999). Environmental concerns regarding the potential for radionuclide contamination of ground water from the accident have prompted additional investigations, including this investigation, of the environmental fate of any unrecovered Pu. An additional concern was the possibility that radionuclides might have migrated as colloids suspended in the ground water. Colloidal transport of Pu has been documented at other sites where Pu has been released to the environment (Penrose and others, 1990; Harnish and others, 1995). The Kirkwood-Cohansey aquifer system, composed of fine to coarse quartz sand, has poor sorption capacity and contains acidic water (Szabo and others, 1997). These two factors strongly contribute to the documented mobility of naturally occurring radionuclides (primarily radium (Ra)) in the water from this aquifer system (Kozinski and others, 1995; Szabo and others, 1997). Colloids with positive surface charge can be mobile in acidic environments (Seaman and others, 1995). High concentrations (higher than 60 mg/L) of colloids also have been found in water samples from this aquifer system collected at some sampling sites (Ryan and Gschwend, 1990). Hence, concern regarding Pu mobility as colloids in the aquifer system is warranted.

The U.S. Geological Survey (USGS), in cooperation with the U.S. Air Force (USAF), conducted a study to evaluate the use of a stringent sampling protocol to determine the presence of radionuclides in the Kirkwood-Cohansey aquifer system near the Facility as a result of the fire of 1960. The field-sampling experiment was developed by the USGS and the USAF to evaluate the effectiveness of the low-flow sampling technique for collecting representative samples from infrequently used observation wells for determination of trace-element and radionuclide concentrations. The field-sampling experiment facilitates the characterization of changes in particulate concentration during well purging with turbidity as a surrogate, the recovery of sediment settled to the bottom of observation wells for chemical analysis, and the characterization of the total (including the particulate), dissolved, and colloidal phases of constituents in water samples upon stabilization of turbidity through the use of various filtration and ultrafiltration techniques. The radionuclide data obtained and the sampling methods used in this investigation can be used to address environmental and regulatory concerns regarding potential radionuclide contamination in the subsurface. The stringent sampling protocol was carefully followed and results documented to avoid potentially biased analytical results from samples. In addition, determination of the particulate, colloidal, and dissolved phase concentrations of the radionuclides in ground water by means of filtration and tangential-flow ultrafiltration in conjunction with the low-flow sampling method provides increasingly accurate information of the nature of the mobile phase relative to previous sampling techniques.

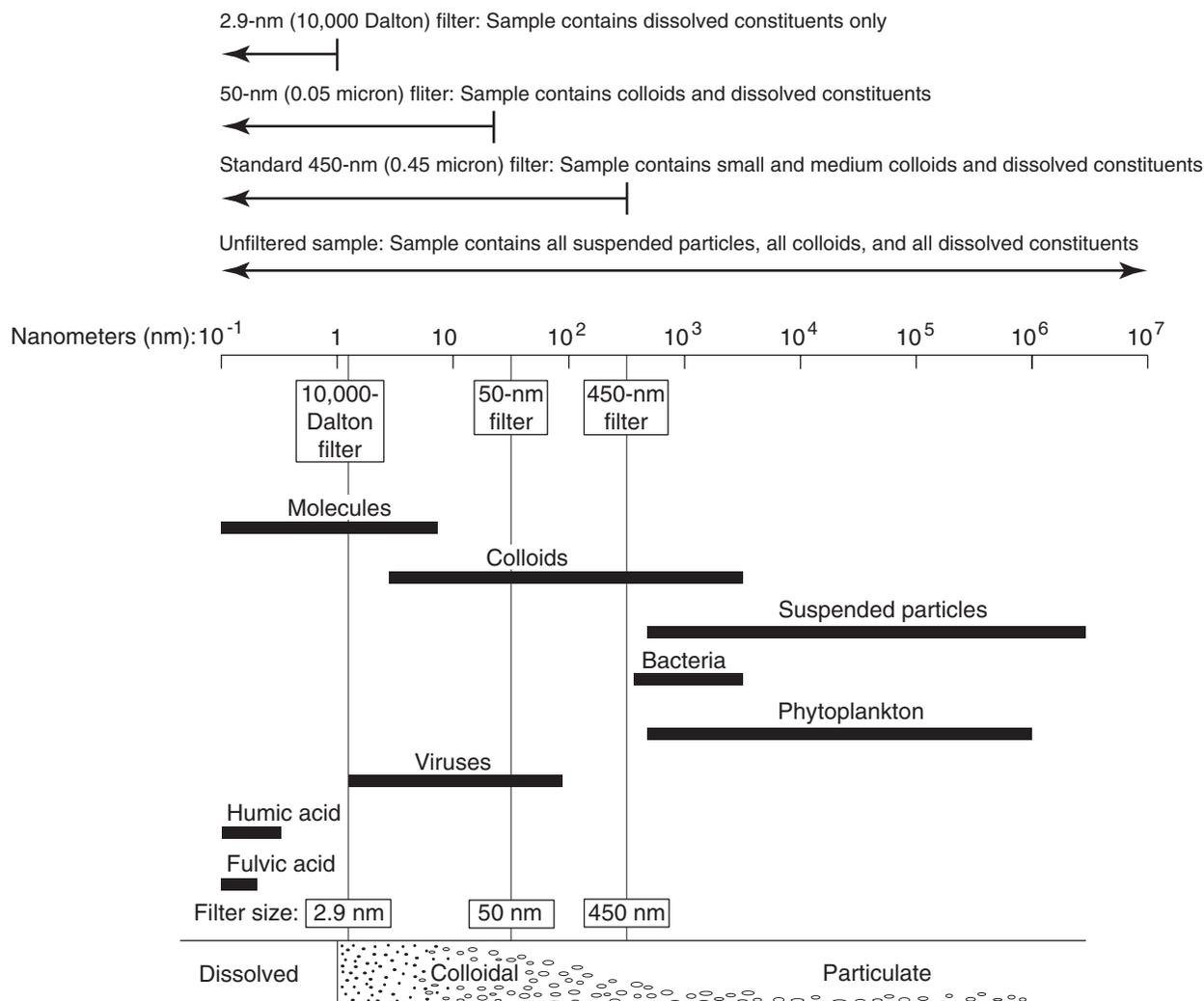
#### Review of Previous Radiochemical Data

During sampling programs conducted at the Facility during 1985–94 by contractors, filtered and unfiltered water samples were collected from observation wells completed in the Kirkwood-Cohansey aquifer system and analyzed for concentrations of gross alpha- and beta-particle activity and isotopes of Pu. Limited concentration data were evaluated for isotopes of uranium (U), thorium (Th), americium (Am), and cesium (Cs). In some cases, the data indicated alpha- and beta-particle activity greater than background activity. Various measurements of concentrations of Pu and U isotopes were reported but were not reproducible in laboratory split samples or in repeated field-sampling efforts. A comparison of the analytical results of filtered and unfiltered samples indicated that the higher concentrations of all the isotopes were associated with unfiltered samples. This difference indicates the possible occurrence of colloidal transport of the radionuclides in the ground water at the Facility.

During the previous sampling programs, sampling techniques were not well documented and did not include consistent protocols; the techniques allowed for variations in the amount of particulate matter in the samples, which led to poor reproducibility of, and possibly high bias in, the analytical results. The unfiltered samples were collected by means of a technique called bailing. Bailing for a water sample stirs the bottom sediment into the water column in the well. This stirring can introduce into the sample substantial amounts of particulate matter that had settled to the bottom of the well but were not actually mobile in the aquifer system. Such particulate material is not a mobile colloid and is likely to have a particle size greater than the standard 0.45- $\mu\text{m}$  (micron) filter typically used for ground-water sampling (fig. 3). Bailing also can cause large variations in concentrations of particles and trace elements between samples from the same well because of variation in the amount of agitation during sample collection. Large amounts of particulate material in water samples from wells at the Facility are noted in a qualitative sense in the contractor reports on the sampling studies but are not documented in a quantitative sense.

#### Purpose and Scope

This report presents a discussion of the presence of radionuclides in the Kirkwood-Cohansey aquifer system at the Facility as a result of human activities and a description of a stringent sampling protocol and equipment designed to obtain water samples that are representative of water in the aquifer system from 10 observation wells. The sampling protocol was designed to minimize turbidity in the water samples so that an accurate assessment could be made of the presence of particulate, colloidal, and dissolved-phase concentrations of radionuclides. The water samples, along with bottom-sediment samples from eight observation wells, were analyzed for isotopes of plutonium, americium, uranium, and thorium to determine whether these radionuclides are present in the Kirkwood-Cohansey aquifer



**Figure 3.** Size classification of aquatic particles and effective pore sizes of selected filters.

system at the Facility in concentrations greater than background. Gross alpha-particle and beta-particle activity were measured for comparison with those from previous studies conducted during 1985–94 for the purpose of characterizing background conditions. Concentrations of radionuclides present in water samples and in bottom-sediment samples collected during the current study are shown in tables and figures.

### Site Hydrogeology

The water-table aquifer that underlies the Facility is 100 ft thick and is composed predominantly of unconsolidated sand of the Kirkwood and Cohansey Formations. Together, these formations compose the Kirkwood-Cohansey aquifer system. This aquifer system, a major regional aquifer system in the Coastal Plain of New Jersey, thickens considerably southeast of

the Facility. The regional extent and thickness of this aquifer system was mapped and described in detail by Zapecza (1989). The Cohansey Sand, middle Miocene in age, is a marginal marine deposit composed of a light-colored medium- to coarse-grained quartz sand with some gravel and silt (Zapecza, 1989). The Kirkwood Formation, lower to middle Miocene in age, is composed of clays interbedded with sand and gravel in coastal areas that grade to a fine- to medium-grained quartz and silty sand inland.

The predominant source of recharge to the Kirkwood-Cohansey aquifer system is precipitation that falls directly onto the aquifer system outcrop. Ground water flows from topographic highs to streams along both shallow and deep flow systems (Rhodehamel, 1973). Ground-water flow to deeper confined aquifers (below the Kirkwood-Cohansey aquifer system) in the area is restricted by a regionally extensive confining unit which is hundreds of feet thick.

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The ground-water flow system of the Kirkwood-Cohansey aquifer system generally can be divided into shallow local-flow systems and deeper regional-flow systems (Rhodehamel, 1973). Actual ground-water flow patterns probably are more complex than the conceptualized patterns and are affected by local heterogeneities in the aquifer material and by seasonal changes in precipitation, evapotranspiration, and water use. An example of the effects of aquifer-material heterogeneities on the orientation of flow paths in the aquifer system is given by Rice and Szabo (1997). About half the water that enters the aquifer system as recharge in a typical first-order stream basin adjoining a surface-water divide is discharged to the nearby stream within about 20 years (Rice and Szabo, 1997). The Facility (fig. 1) is situated within such a first-order stream basin adjacent to a major surface-water divide. The aquifer system is highly conductive; results of a regional-scale numerical flow model calibrated for an area to the north of the Facility indicated that horizontal conductivity is 80 to 100 feet per day (Nicholson and Watt, 1997).

Currently (2000), contamination of the water supply is not an issue at or near the Facility site because the nearest water-supply wells within the aquifer system are located miles from the Facility. On the basis of the measured water-table altitude at the Facility, actual ground-water flow is predominantly from the area of the highest altitude on the Facility towards the areas of lower altitude (areas of discharge) in the adjoining wetlands and the Success Branch to the east (fig. 2).

Because of the presence of the Pine Barrens Preserve in much of the southeastern part of the State (fig. 1), land use within the area underlain by the outcrop of the Kirkwood-Cohansey aquifer system in this region is largely undeveloped, especially near the Facility. Urbanization has encroached appreciably on both agricultural and previously undeveloped areas within the past decade; this urbanization has occurred mostly in the southwestern and northeastern parts of the aquifer system outcrop area, not in the vicinity of the Facility.

### Detection of Colloids, Radionuclides, and Trace Elements in Ground Water

The concentrations of radionuclides and other trace elements can be substantially greater when particulate matter is present in unfiltered samples than when it is absent because many of these constituents have a strong tendency to sorb onto particulates. The analysis of samples with large amounts of particulate material can be difficult as a result of "matrix effects" that often result in poor precision and interferences. These factors can, in turn, cause measured concentrations of constituents in samples with abundant particulate matter to exceed concentrations in samples without abundant particulate matter. The variability of the quantity of particulates from sample to sample is likely the major factor that made it difficult, if not impossible, for the contract laboratory to reproduce analytical results, indicating the need to use consistent, strict, and appropriate sample-collection protocols.

The radioactive material Pu is a component of nuclear weaponry but also can be present in the environment from global atmospheric fallout to which the nuclear power industry, as well as nuclear weapons testing, has contributed. The isotope Pu-239 readily undergoes nuclear fission when a neutron collides with the nucleus, and the nucleus releases small product nuclides as well as two or three additional neutrons, which can then continue to fuel fission reactions. The isotope is, therefore, a necessary component of nuclear weapons fueled by Pu. Weapons-grade Pu contains lesser amounts of Pu-240 relative to Pu-239 than is typical for the ratio of these two isotopes in global fallout (Liator, 1999). Pu-240 and Pu-239 are more abundant than Pu-238 at nuclear-weapons facilities. Weapons-grade Pu contains almost no Am-241 (Hulse and others, 1999) because of rigorous purification and concentration of the Pu-239 isotope. The Am-241 to Pu-239 isotope activity ratio increases after the purification process. The Am-241 originates from in-growth from the minor amounts of the Pu-241 isotope (about 1 percent of Pu in weapons) that decay with a 14.4-year half-life.

All isotopes of U are naturally occurring and are ubiquitous in soils, rock, and most waters. Isotopes of U are found at low concentrations (much less than 1 pCi/g) in the sediments that form the Kirkwood-Cohansey aquifer system (Szabo and others, 1997); correspondingly, concentrations of U are also low in the water from the aquifer (less than 1 µg/L). The naturally occurring isotope of U, U-235, is also a component of nuclear weapons because it readily undergoes fission. Because U-238 is far more abundant than U-235, the U-235 has to be concentrated in the laboratory, resulting in U-235-rich material known as "enriched uranium." The process used to enrich U-235 also concentrates the U-234 isotope. Distinguishing naturally occurring U from industrially altered contaminants from weapons can be difficult unless anomalous U-234:U-238 isotopic ratios far greater than the natural background ratio of about 1.0 are encountered. The natural weathering process may slightly enrich U-234 relative to U-238 in water but rarely by more than a factor of 2 (Osmond and Cowart, 1976).

Radium is a progeny of a radioactive decay of U and is soluble in acidic water. Radionuclides of Ra are present in water from the Kirkwood-Cohansey aquifer system in widespread areas, often at concentrations high enough to cause concern for health risk (Szabo and others, 1997). The Ra likely is mobilized by weathering. The presence of elevated amounts of Ra in the water also results in high gross alpha-particle radioactivity (Kozinski and others, 1995). Because the water could contain substantial amounts of alpha radioactivity even under natural conditions, the presence of elevated alpha radioactivity alone is not an indicator of manmade contamination.

Considerable improvements in field-sampling procedures and laboratory analytical techniques and technology in the 1990s have led to the increased capability to detect and quantify concentrations of colloids, radionuclides, and trace elements in water samples, including ground-water samples with complex matrix. These improvements were incorporated, where possible, into the field-sampling experiment and are briefly summarized here.

## Size Classification of Aquatic Particles

Water in the environment can contain large quantities of foreign particles of various sizes, shapes, and densities. Some are small in size, low in density (close to that of water), and of such shape that they do not obey Stokes' Law of settling (formulated in 1845); they remain in suspension even in still water (see Gibbs and others, 1971, for further discussion).

Colloids have generally been defined as those particles about 0.002  $\mu\text{m}$  (micron) (2 nm (nanometers)) to 1  $\mu\text{m}$  (1,000 nm) in size that do not settle from suspension in still water. Therefore, colloids can often pass through many pore sizes of filters (Kennedy and others, 1974) but ultimately are retained on a 10,000-Dalton ultrafilter, which has a nominal pore size of 0.0029  $\mu\text{m}$  (fig. 3). A Dalton is defined as being equal to a predefined nominal molecular weight (NMWL). The nominal pore size of a filter is defined operationally by the size of the particles which are retained with 98-percent efficiency during the filtration process. The pore sizes of 10,000 and 100,000 Daltons correspond to nominal pore sizes of about 0.0029 and 0.0062  $\mu\text{m}$ , respectively.

Particles other than colloids become suspended at various rates of water flow. In general, these suspended particulates are larger than colloids and are greater than about 0.45  $\mu\text{m}$  in diameter (fig. 3), though exceptions occur.

The terms colloid and particulate are size classifications and do not define the chemical composition or chemical reactivity of the particle. The size range of colloids, which do not settle from still water, overlaps that of particulates, which do. For this sampling program, particulates were defined as all particles retained by the 0.45- $\mu\text{m}$  filter and colloids as particles retained by the 10,000-Dalton ultrafilter. These definitions are consistent with the terminology used by Harnish and others (1995). The chemical capability of colloids to transport trace elements and radionuclides has been recognized for many years (Gibbs, 1973; Gibb and others, 2000; Hoffman and others, 1981; Penrose and others, 1990).

Trace elements are present in ground water as solutes and in association with particles, particularly colloids. The historical operational definition of "dissolved" as the capability to pass through a 0.45- $\mu\text{m}$ -pore filter is commonly used for convenience and to maintain historical continuity despite clear evidence that these filters allow passage of some particles and colloids (Kennedy and others, 1974). As a result, data obtained from the analysis of water that has passed through a 0.45- $\mu\text{m}$ -pore filter does not necessarily represent concentrations of dissolved trace elements only.

## Mobility of Colloids, Radionuclides, and Trace Elements in Ground Water

Few sites or wells are present for which both the truly dissolved component and the mobile particulate or colloidal fraction of trace-element or radionuclide contaminants are well characterized. The presence of abundant colloids in shallow

ground water in some geochemical environments was demonstrated by Ryan and Gschwend (1990) with samples collected from the Kirkwood-Cohansey aquifer system. Harvey and others (1993) also were able to recover what they considered mobile colloids from pumped wells. Ryan and Gschwend (1990) indicated that 10 to 20 casing volumes of water had to be purged before stable turbidity was achieved and colloid concentrations were considered reliable. Results of their field investigation indicated that low colloid concentrations (low turbidity) could be the norm in oxidizing environments. Concentrations of particles measured in their field experiment in the oxidizing environment of the Kirkwood-Cohansey aquifer system were less than 1 mg/L, which is consistent with most of the colloid-concentration data tabulated for other sites by Kearn and others (1992). Colloid concentrations as high as 60 mg/L have been documented, however, by Ryan and Gschwend (1990) in water from sandy Coastal Plain aquifers under anoxic conditions; the colloids ranged in size from 0.03  $\mu\text{m}$  to about 2  $\mu\text{m}$ . Microspheres with a maximum diameter of 1 to 2  $\mu\text{m}$  have been recovered from sand aquifers by Harvey and others (1993) and Bales and others (1997), who interpreted this result to indicate that transport of colloids of this size occurs in the environment. Bales and others (1997), however, applied appreciable stress to the aquifer in terms of rapid pumping (30 L/min (liters per minute)), which could lead to a flow velocity much greater than the typical flow velocity in the environment.

Ryan and Gschwend (1992) hypothesize that the concentration and mobility of colloids depends on the geochemistry of the aquifer, especially the oxidation-reduction potential. Colloids with net positive surface charge are as likely to be mobile in water with acidic conditions and high concentrations of dissolved solids as are dissolved cationic trace elements (Seaman and others, 1995) and radionuclides with positive charge. High concentrations of dissolved solids, especially in association with acidic water, also tend to increase the mobility of dissolved trace elements because the available sorption capacity of aquifer solids decreases in acidic water; therefore, sorption sites are more likely to be completely saturated by the large amount of cations present in mineralized water. For example, the mobility of radium (Ra), a naturally occurring radionuclide present as a divalently charged cation under almost all geochemical conditions (Langmuir and Riese, 1985), was assessed by Kozinski and others (1995) and Szabo and others (1997) in filtered samples from the Kirkwood-Cohansey aquifer system; the mobility likely is a result of acidic conditions and the presence of moderately high dissolved solids concentrations (250 mg/L). Concentrations of combined radium (Ra-228 plus Ra-226) were greater than the 5 pCi/L (picocuries per liter), the Maximum Contaminant Level (MCL), in 37 percent of 88 samples collected by Kozinski and others (1995). Colloids from sandy Coastal Plain aquifers have been found to have a large organic carbon component (Ryan and Gschwend, 1990). The organic carbon component could affect the transport characteristics of organic contaminants and colloids as well as those of radionuclides and trace elements (Ryan and Gschwend, 1992). Because pH and oxidation-reduction potential also affect the speciation

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of truly dissolved U, Am, and Pu (Lemine and Tremaine, 1980), and thereby affect the mobility of these constituents, the pH and the dissolved oxygen content are important characteristics to determine in the field whether truly dissolved-phase or colloidal transport is being investigated. Penrose and others (1990) and Harnish and others (1995) discuss colloidal transport of Pu and Am and report that Pu is more likely than Am to be transported in the colloidal and particulate phase.

### Tangential-Flow Ultrafiltration as a Technique for Removal and Characterization of Colloids in Ground Water

Further characterization of both the colloidal and dissolved phases of trace elements and radionuclides and their transport in ground water is needed for sites where such contamination has been found. This characterization is especially important in the Coastal Plain where the typical shallow aquifer is unconfined and acidic and, therefore, is ideal for cationic and colloidal mobility (Seaman and others, 1995). Few methods exist for separating colloids of various sizes from water, however. The equipment used is cumbersome, often produces artifacts, and generally is not portable (Buffle and Leppard, 1995).

Tangential-flow ultrafiltration overcomes all the difficulties given above for separating colloidal fractions from water and produces a sample that contains only dissolved constituents or that includes colloids of a predetermined size range. In tangential-flow ultrafiltration, most of the water passes across, rather than through, the filter, and the thickness of the diffusion layer of the filter membrane, where colloids can coagulate, is minimized by the high flow rate parallel to the membrane. Particles, whether suspended in the water or formed by colloid coagulation, generally do not build up on the filter. Particles are moved by the flow across the filter surface rather than forced onto the surface of the filter material. The general absence of particles on the filter is an advantage because the effective pore size changes only to a minimum degree as filtering proceeds. Therefore, the process increases sample comparability, increases confidence in the quantification of colloid concentrations and of colloidal and non-colloidal concentrations of trace elements, and results in reliable data. Particle build up on the commonly used plate and capsule filters can reduce the effective pore size of the filters (Horowitz and others, 1996).

The water collected after passing across the tangential-flow ultrafilter is the desired sample if characterization of the colloidal component of a specified size range (greater than the nominal pore size of the filter) is the objective of sample collection. The water collected after passing through the tangential-flow ultrafilter is the desired sample if composition of water without colloids of the specified size range is the objective. The use of tangential-flow ultrafiltration in the field has become increasingly commonplace because the technique allows for the removal of particles with diameters greater than or equal to 0.0029  $\mu\text{m}$  (or about 10,000 Daltons). Terms used to define aspects of the tangential-flow ultrafiltration process are defined

in the Glossary at the back of the report, and are used throughout this report.

Quantification of the concentrations of solutes (in this study, defined as passing through a tangential-flow ultrafilter with nominal pore size of 10,000 Daltons) is desirable for four reasons. First, solutes generally are considered biologically available to humans and other biota, whereas particulate-bound trace elements may or may not be biologically available. Therefore, quantification of solute concentrations provides a minimum measure of biological availability. Because biologically available concentrations of trace elements, especially radionuclides, are identified as human-health risks upon ingestion, the quantification of solute concentrations is an important goal for any monitoring program concerned with health effects. Second, samples containing only solutes may be more representative of trace elements that actually move in ground water than unfiltered samples, especially if the sample was collected without strict adherence to rigorous purging and sampling protocols (Gibs and others, 2000). Particulates in ground-water samples are commonly an artifact of high-flow velocities induced near the well bore during well purging (Kearl and others, 1992; Backhus and others, 1993; Gibs and others, 2000) and may be composed, in part, of particulate material that was introduced into the aquifer matrix during the drilling of the well. A third reason for determining solute concentrations is to further the understanding of processes that affect trace-element and radionuclide concentrations dissolved in ground water. A final, fourth, benefit of using ultrafiltration or tangential-flow ultrafiltration is the removal of biota that can change the chemical species in samples, such as nitrogen, iron, and arsenic species.

Trace-element-bearing colloids or particulates can be artificially mobilized during the well-purging process in many ways, including agitation of the standing water column in the well during submersion of the pump and increased shear in the aquifer from overpumping (Kearl and others, 1992; Backhus and others, 1993). The artificially mobilized particulates could be incorporated into water samples during collection. For measurement of dissolved constituents, an objective of the sampling process is to decrease the concentration of artificially mobilized colloids and the associated turbidity, not to increase it. Oneacre and Figueras (1996) demonstrated that for a suite of 15 trace elements recoverable from whole water, the detection rate was 17 percent greater in ground-water samples with turbidities of 25 to 49 nephelometric turbidity units (NTU) than in samples with turbidities less than or equal to 24 NTU. Turbidity (assumed to be primarily from artificially mobilized particulates) directly correlated with trace-element concentrations in sequentially collected raw-water samples (Gibs and others, 2000). Artificially mobilized particulates can be removed through standard filtration techniques, but filtration alone results in the presence of sampling artifacts from the removal of particulates or colloids that actually were mobile in the ground water (Horowitz and others, 1996). If colloids themselves are to be separated and characterized, ideally, the presence of artificially mobilized particulates in the water must be minimized.

The low-flow sampling technique is a natural fit with tangential-flow ultrafiltration because it is designed to minimize the presence of artificially mobilized particulates and colloids. The low-flow sampling technique (Puls and Barcelona, 1995) generally has been recommended to minimize the presence of artificially mobilized particulates in unfiltered water samples. The low-flow rates also minimize colloid coagulation during the tangential-flow ultrafiltration process (Buffle and Leppard, 1995).

Field-sampling techniques that rigorously ensure the integrity of the collected filtered and unfiltered ground-water samples are required. State-of-the-art analytical techniques are not useful if the sample-collection and -handling procedures introduce random trace-element contamination or artifacts. Techniques for the collection and handling of samples for precise and unbiased analysis of trace elements at low concentrations in ground water have been refined and improved (Ivahnenko and others, 1996; 2001). Improvements to the ground-water sampling technique for low-concentration trace elements includes rigorous cleaning of sampling equipment, increased care during sample handling, and strict quality assurance, in addition to the low-flow-sampling technique to minimize artifacts produced by the mobilization of particulates during the well-purging and sampling process.

## Methods of Radiochemical Sampling

The field-sampling experiment used in this investigation was designed to determine the presence of any particulate, colloidal, and dissolved-phase concentrations of radionuclides in water samples from the water-table aquifer that might be attributable to the fire of 1960. Water samples were collected from 10 observation wells. Isotopes of Pu, Am, U, and Th that could be associated with the warhead were selected as the constituents to be analyzed. Gross alpha-particle and beta-particle activity were measured to provide an overall screen for radionuclides in ground water and for comparison with results from previous studies and with background data provided by Szabo and others (1997). Analysis for Th isotopes was completed for the first five, but not the last five, wells sampled. Results of analysis for radionuclides in soil samples at the Facility indicated that Th concentrations and isotope ratios in surface soils were typical for the region and did not represent radionuclide contamination (Steven Raddemacher, U.S. Air Force, oral commun., 1999).

In order to address environmental and regulatory concerns, specific attention was placed on size fractionation during sampling to determine if any radioactive contaminants were sorbed to potentially mobile particles (colloids) in ground water, and to particles that may settle from the ground water. Settled particulates at the bottom of the well also were collected and analyzed.

## Design of Field-Sampling Experiment

The development of the field-sampling experiment took into account the large amount of particulate matter observed in all the previous radiochemical sampling at the Facility. The sampling methods were required to result in samples that contain a true representation of both particle and radionuclide concentrations within the water of the aquifer system. It was not known whether elevated concentrations of radionuclides (elevated above background levels) reported for some of the previously collected unfiltered samples resulted from the presence of immobile particles introduced from land surface during well drilling that settled to the bottom of the well, from particles from the aquifer materials that were artificially mobilized by well purging or turbulence from the use of bailers, from particles mobile in the water as colloids, or simply from analytical problems that were compounded by matrix effects in turbid samples.

The low-flow sampling technique (Puls and Barcelona, 1995) was selected to minimize the presence of artificially mobilized particulates or colloidal material in unfiltered water samples. Changes in particulate concentration during well purging were characterized by monitoring turbidity. Sediment that settled to the bottom of the observation wells was collected for chemical analysis. Water samples that represent the total (unfiltered), truly dissolved, and colloidal phases of radionuclides were collected upon stabilization of turbidity through the use of various sequential filtration and tangential-flow ultrafiltration techniques. Colloids are retained on filters with nominal pore sizes that are smaller than the diameter of the colloidal particles, such as the 10,000 Dalton filter. The colloids are assumed to be of a smaller size than the particulates and are assumed to pass through the 0.45  $\mu\text{m}$  but not the 10,000 Dalton filter. It is assumed that only dissolved constituents pass through the 10,000 Dalton filter.

## Sampling Network

Ten previously installed observation wells were selected for sampling (fig. 2; table 1). Information on the construction, altitude, and location of wells included in this report is stored under a 6-digit unique well number in the Ground-Water Site Inventory database maintained by the USGS. This well number consists of a 2-digit county code followed by a 4-digit sequence number. The county code used in this report is 29 (Ocean County). For example, well number 29-1379 is the 1,379th well inventoried in Ocean County. Well-construction data in the tables in this report are sorted by well number, but water-quality information presented in tables is sorted by well depth, not by well number.

Wells 29-1203, 29-1371, 29-1372, 29-1374, 29-1375, 29-1377, and 29-1379 were installed during 1986–87 for the primary purpose of determining the degree of radionuclide contamination in water at the Facility. The previously obtained radionuclide data for these wells were reviewed and found to be highly variable and without documentation of purging

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**Table 1.** Well-construction data and water levels on March 30, 2000, for selected wells screened in the Kirkwood-Cohansey aquifer system at or near the BOMARC Missile Facility, Ocean County, New Jersey.

[--, data not available; NAD27, North American Datum of 1927; NAD83, North American Datum of 1983; \*, water samples collected from this well; USGS, U.S. Geological Survey. Altitudes are reported relative to the National Geodetic Vertical Datum of 1929 (NGVD29).]

Well name	USGS well number	New Jersey permit number	Latitude (decimal units)	Longitude (decimal units)	Datum	Altitude of land surface (feet above NGVD29)	Depth of open interval (feet below land surface)		Well diameter (inches)	Water level (feet above NGVD29)
							Top	Bottom		
PU6	291203*	28-17921-8	400204	742651	NAD27	166.24	35	50	2	127.7
BM3	291209	28-17925-1	400145	742628	NAD27	141.10	10	25	2	127.55
MW101	291370*	28-27380	400152.54	742633.85	NAD27	127.11	32	42	2	127.75
PU5	291371*	28-18291-0	400201.35	742642.5	NAD27	166.4	37	52	2	127.72
PU2	291372*	28-17919-6	400201.45	742636.49	NAD27	171.71	43	58	2	127.42
PU1	291374*	28-17918-8	400205.42	742631.66	NAD27	180.14	53	68	2	127.15
PU3	291375*	28-17920-0	400206.62	742636.24	NAD27	174.71	47	62	2	127.35
MW2	291376*	--	400206.34	742621.73	NAD27	148.9	79.6	89.6	4	--
PU7	291377*	28-18292-8	400206.34	742622.40	NAD27	150.06	22	37	2	126.45
MW4	291378*	--	400207	742615	NAD27	137.54	103.6	113.6	4	--
MW49	291379*	28-17922-6	400210.56	742632.83	NAD27	164.7	38	53	2	127.085
MW-104	291382	28-27393-1	400149	742618	NAD27	133.42	10	20	2	126.98
BM-4	291383	28-17933-1	400154	742619	NAD27	138.21	9	24	2	126.81
MW-08	291384	--	400158	742610	NAD27	129.04	9.7	24.7	4	126.85
MW-105	291386	28-27394-0	400158	742621	NAD27	147.01	18	28	2	126.765
MW-11	291387	--	400203	742605	NAD27	126.21	34	49	4	125.13
MW-07	291388	--	400203	742609	NAD27	132.13	27	42	4	126.195
MW-107	291389	28-27396-6	400206	742622	NAD27	148.78	52	62	2	126.505
MW-108	291390	28-27411	400207	742615	NAD27	138.58	30	40	2	125.81
MW-10	291392	--	400210	742601	NAD27	126.35	35.4	50.4	4	123.65
MW-06	291393	--	400210	742616	NAD27	136.13	43	58	4	125.914
MW-X48	291394	28-17923-4	400210	742621	NAD27	143.65	17	32	2	126.24
MW-14	291395	--	400211	742557	NAD27	122.55	40	50	4	122.18
MW-15	291396	--	400211	742557	NAD27	122.34	6	16		122.1
MW-01	291397	--	400214	742601	NAD27	126	40.4	55.4	4	122.87
MW-12	291398	--	400215	742555	NAD27	122.41	40	50	4	121.325
MW-13	291399	--	400215	742555	NAD27	122.41	5	15	4	121.445
MW-05	291400	--	400215	742613	NAD27	131.25	41.5	56.5	4	125.315
MW-09	291401	--	400220	742602	NAD27	124.84	44.7	59.7	4	122.295
BM-1	291434	28-17924-2	400149.39	742629.91	NAD83	142.81	12	27	2	127.48

**Table 1.** Well-construction data and water levels on March 30, 2000, for selected wells screened in the Kirkwood-Cohansey aquifer system at or near the BOMARC Missile Facility, Ocean County, New Jersey.—Continued

[--, data not available; NAD27, North American Datum of 1927; NAD83, North American Datum of 1983; \*, water samples collected from this well; USGS, U.S. Geological Survey. Altitudes are reported relative to the National Geodetic Vertical Datum of 1929 (NGVD29).]

Well name	USGS well number	New Jersey permit number	Latitude (decimal units)	Longitude (decimal units)	Datum	Altitude of land surface (feet above NGVD29)	Depth of open interval (feet below land surface)		Well diameter (inches)	Water level (feet above NGVD29)
							Top	Bottom		
MW-X45	291435	28-17930-7	400150.79	742628.59	NAD83	148.73	20	35	2	127.635
MW-X46	291436	28-17931-5	400151.39	742628.12	NAD83	148.11	20	35	2	127.635
MW-X44	291437	28-17929-3	400151.65	742629.17	NAD83	150.17	20	35	2	127.66
MW-17	291438	28-13807	400152.63	742628.92	NAD83	153.38	14	29	4	127.99
MW-102	291439	28-27391	400152.93	742628.41	NAD83	153.86	50	60	2	127.49
MW-X16	291440	28-13817	400153.32	742628.35	NAD83	154.05	21	36	4	127.905
MW-X43	291441	28-17928-5	400153.67	742627.04	NAD83	152.96	25	40	2	127.42
MW-X42	291442	28-17927-7	400154.32	742626.97	NAD83	153.86	22	37	2	126.735
MW-X41	291443	28-17926-9	400155.40	742629.69	NAD83	157.98	27	42	2	127.75
MW-103	291444	28-27392	400156.12	742627.37	NAD83	157.71	25	35	2	127.77
BM-2	291445	28-18289-8	400158.59	742622.45	NAD83	151.81	21.5	36.5	2	126.97
MW-X47	291446	28-17932-3	400158.79	742625.31	NAD83	167.17	37	52	2	127.45
MW-106	291447	28-27395	400201.66	742623.37	NAD83	170.28	40	52	2	126.925

conditions or evidence of physical stabilization of properties at the time of sample collection. A water-level synoptic study for the purpose of determining the potentiometric surface was completed in March 2000 (fig. 2). A reconnaissance water-level synoptic study to determine which wells would be sampled was completed as part of the project-planning phase in the autumn (October 1998) preceding the sample collection when no precipitation had fallen for at least 7 days (results not shown). Water levels that provided the basic data for the potentiometric surface were measured with an accuracy of  $\pm 0.01$  ft by use of a weighted steel tape from a designated measuring point, usually a groove in the top of the well casing with a surveyed altitude within an accuracy of  $\pm 0.1$  ft. Measurements were repeated until two consecutive readings were within an accuracy of  $\pm 0.01$  ft. Additional wells not previously sampled but selected for this study are 29-1370, 29-1376 and 29-1378; the wells were selected on the basis of the synoptic water-level data collected in October 1998 and March 2000 (fig. 2). The remainder of the wells at the Facility were used for water-level measurements (fig. 2; table 1). Samples from the 10 wells selected were collected from August 19, 1999, to February 23, 2000.

Wells 29-1374, 29-1376, 29-1377, and well 29-1378 are situated parallel to the natural ground-water flow path that trends east in this part of the unconfined aquifer and are immediately downgradient from the accident site. Well 29-1378 is

500 feet downgradient from the eastern boundary of the Facility. It was selected for sampling because the open interval at a depth of 110 feet (table 1) is positioned near the base of the Kirkwood-Cohansey aquifer system. Well 29-1378 is completed in the deepest part of the aquifer and provides a control point to determine whether any radioactive contaminant has moved off site at depth. Well 29-1377, a shallow well open from 22 to 37 feet below land surface, and well 29-1376, a deep well open from about 80 to 90 feet, are nested; they were selected to provide information on radionuclide concentrations with depth in the aquifer system. Well 29-1379, which is offset (to the north) from the flow path that trends away from Shelter 204, and well 29-1370, which is about 0.25 miles south of Shelter 204, were selected to provide potential background information. Well 29-1370 is downgradient from the stormwater culvert located on the west side of the major local roadway, Route 539 (fig. 2). This well was sampled to determine whether any ground-water contamination is present in this part of the Facility from runoff into the adjacent drainage ditch during the fire fighting. Wells 29-1203, 29-1371, and 29-1372 are adjacent to the drainage ditch to the west near Shelter 204. Well 29-1373, though near Shelter 204 (about 200 feet, but not shown in fig. 2), was not sampled because it was determined during well redevelopment that this well did not yield sufficient quantities of water to fill the volume requirements for sample collection.

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### Preparation for the Field-Sampling Experiment

Low-flow sampling is intended to produce representative samples with minimal artifacts from artificially mobilized particles. It is nevertheless assumed that the sampled wells are properly developed. The previous collection of particle-laden samples and the absence of written records describing well development indicated that adequate well development may not have occurred. Therefore, the observation wells were redeveloped, settled sediment was removed, and the sampling pump was placed in the screened area after geophysical logging.

### Well Development and Settled-Sediment Sampling

Before sampling began in October 1999, the wells were developed sufficiently to lower the water turbidity to levels of less than 5 NTU in each well. Guidelines for successful well development consisted of removal of sediment settled in the bottom of the well and the development of steady pumping rates greater than those to be used for sampling, that is, much greater than 0.5 L/min (liters per minute) with turbidity less than 5 NTU. Conditions of well redevelopment are listed in table 2.

The observation wells had not been purged or sampled in more than 10 years in some cases. Large amounts of sediment most likely settled to the bottom over time. In addition, supporting documentation describing initial well development was not available. Inadequate well development routinely leads to difficulty in sampling because of the presence of a large amount of settled sediment (Koterba and others, 1995). Sediment in the bottom of each well ranged in thickness from 0.05 to 5.75 ft (table 2). This thick deposit of sediment was considered to be a major factor contributing to the high particulate matter in turbid water collected during previous sampling programs. This particulate matter caused water turbidities in the bailed, unfiltered sample to be higher than actual levels in water from the aquifer system, and the particulate-rich matrix likely was not acceptable for precise analysis.

Before pumping for well development began, sediment from the bottom of each well was removed by collecting it into a stiff 1-inch polyvinyl chloride (PVC) tube with suction applied from a large-volume portable centrifugal pump. A weighted steel tape was used to sound the depth of the well. The difference between the measured depth and the depth from well-construction records (table 2) was estimated as the thickness of the settled sediment, which ranged from about 0.05 to 5.75 ft. The PVC tube was lowered into the well and manually forced down into the sediment layer about 3 inches at a time with the centrifugal pump producing suction. With the pump turned on and producing suction, the PVC tube was manually pulled back to the surface. A ball-type check valve (Brady foot valve FV/SFV 100) attached to the base of the PVC tube prevented back flow and the loss of sediment (fig. 4). Generally, 3 to 12 inches of sediment could be removed at one time using this technique (table 2). At land surface, the check valve was

released. If a sufficient quantity of sediment was retrieved, it was poured into wide-mouth 0.5-L glass-sampling jars for analytical purposes.

Sediment samples from the bottom of all wells except 29-1378 were submitted, mostly in duplicate, for analysis of Pu isotopes 238, 239+240; Am-241; and U isotopes 234, 235, and 238. Bottom sediment was first centrifuged in high-density polyethylene centrifuge bottles at 10,000 revolutions per minute for 20 minutes to separate the sediment from the water. Analytical results of radionuclide concentrations in the settled sediment could provide the worst-case scenario with respect to the degree of contaminant sorption on particulates or particle-borne radiochemical contamination deposited into the well during well construction. (The bottom sediment sample from well 29-1372 was accidentally discarded at the laboratory before analysis was complete.)

Over-pumping rates (American Society for Testing and Materials, 1994) were maintained at about 30 to 40 L/min for a period of about 60 minutes or more, if needed, to develop the wells sufficiently to lower the water turbidity to levels of about 5 NTU or less in each well. The pumping rate was rapidly varied to initiate surging action in wells that did not clear. Turbidity was monitored every 5 minutes by use of a Hach Ratio/X-2100 Portable Turbidimeter using procedures recommended by Wilde and Radtke (1999) and Gibs and others (2000). The pumping of water was accomplished with a portable centrifugal or portable submersible pump. A Grundfos Rediflo-2 pump that was not used for sampling was set nearly in the center of the well screen for the well-development process. The level of the submersible pump during redevelopment is provided, when applicable, in table 2; the pump was not lowered to the bottom of the well for redevelopment purposes.

### Geophysical Logging and Placement of the Sampling Pump

Prior to placement of the sampling equipment, a gamma ray log was run in each well to determine the most permeable section of the screened interval. The logging tool included a 3-inch sodium iodide (NaI) crystal and was lowered and raised in the well bores at 2 ft per minute. The most permeable interval was determined by evaluating gamma ray response for each screened interval; the least radioactive zone was assumed to be the coarsest grained and, thus, most permeable. The dedicated portable Grundfos Rediflo-2 submersible sampling pump was set in the screened interval of each well adjacent to the most permeable interval for a minimum of 24 hours before pumping in accordance with criteria established for low-flow purging (Kearl and others, 1992; Puls and Barcelona, 1995). The level of pump during purging is given in table 3. Once the pump was set, it was not raised or lowered before or during well purging or sampling. Natural gamma ray logs, the screened interval, and the pump setting for collection of water samples are shown in appendix 1.

**Table 2.** Conditions of well redevelopment for sampled observation wells at or near the BOMARC Missile Facility, Ocean County, New Jersey.

[BLS, below land surface; NTU, nephelometric turbidity unit; NA, not available; --, no data; data sorted in order of well depth]

U.S. Geological Survey well number	Well diameter (inches)	Screened interval (feet BLS)	Date of redevelopment (month/day/year)	Altitude of measuring point (feet)	Depth to water (feet BLS)	Casing volume (liters)	Over pumping duration (minutes)	Number of casing volumes purged	Initial over pumping rate (liters per minute)	Final over pumping rate (liters per minute)	Level of pump during redevelopment (feet BLS)	Initial turbidity (NTU)	Lowest turbidity (NTU)	Initial measured depth (feet BLS)	Final measured depth (feet BLS)	Volume of sediment removed (cubic feet)
291377	2	22–37	10/25/99	152.16	23.75	7.36	65	327.6	37.1	37.1	NA	27.3	0.63	34.50	35.90	0.049
291370	2	32–42	11/5/99	129.91	31.59	6.24	79	412.1	32.6	32.6	NA	43.1	.76	41.84	41.89	.0016
291203	2	35–50	10/25/99	168.24	38.93	4.66	60	385.0	29.9	29.9	39.29	79.0	1.01	45.56	46.62	.034
291379	2	37–52	10/22/99	166.97	38.02	8.06	27	126.8	37.9	37.9	NA	5.13	.49	50.48	51.33	.028
291371	2	37–52	10/26/99	168.99	39.03	7.53	100	407.2	30.7	30.7	39.56	169	4.17	49.66	51.46	.058
291372	2	42–57	10/18/99	174.17	NA	7.29	NA	NA	NA	NA	NA	NA	NA	52.91	55.64	--
			10/19/99	174.17	44.51	7.29	135	522.9	1.42	22.7	NA	100	46.0	54.97	56.54	1.176
			10/21/99	174.17	NA	7.29	68	224.9	29.9	8.7	47.54	39.3	7.2	NA	NA	NA
291375	2	47–62	10/21/99	176.92	47.74	7.90	50	192.1	30.3	30.7	50.20	1.88	1.34	55.04	60.79	1.863
291374	2	52–67	10/21/99	182.75	53.29	6.42	57	236.0	33.3	7.57	54.28	4.29	2.10	62.89	63.89	.032
291376	4	80–90	10/28/99	151	21.66	166.9	238	44.38	33.3	17.0	28.62	306	7.63	89.50	89.50	0
291378	4	103.6–113.6	NA	141.6	14.40	244.1	NA	NA	NA	NA	NA	NA	NA	113.6	NA	0

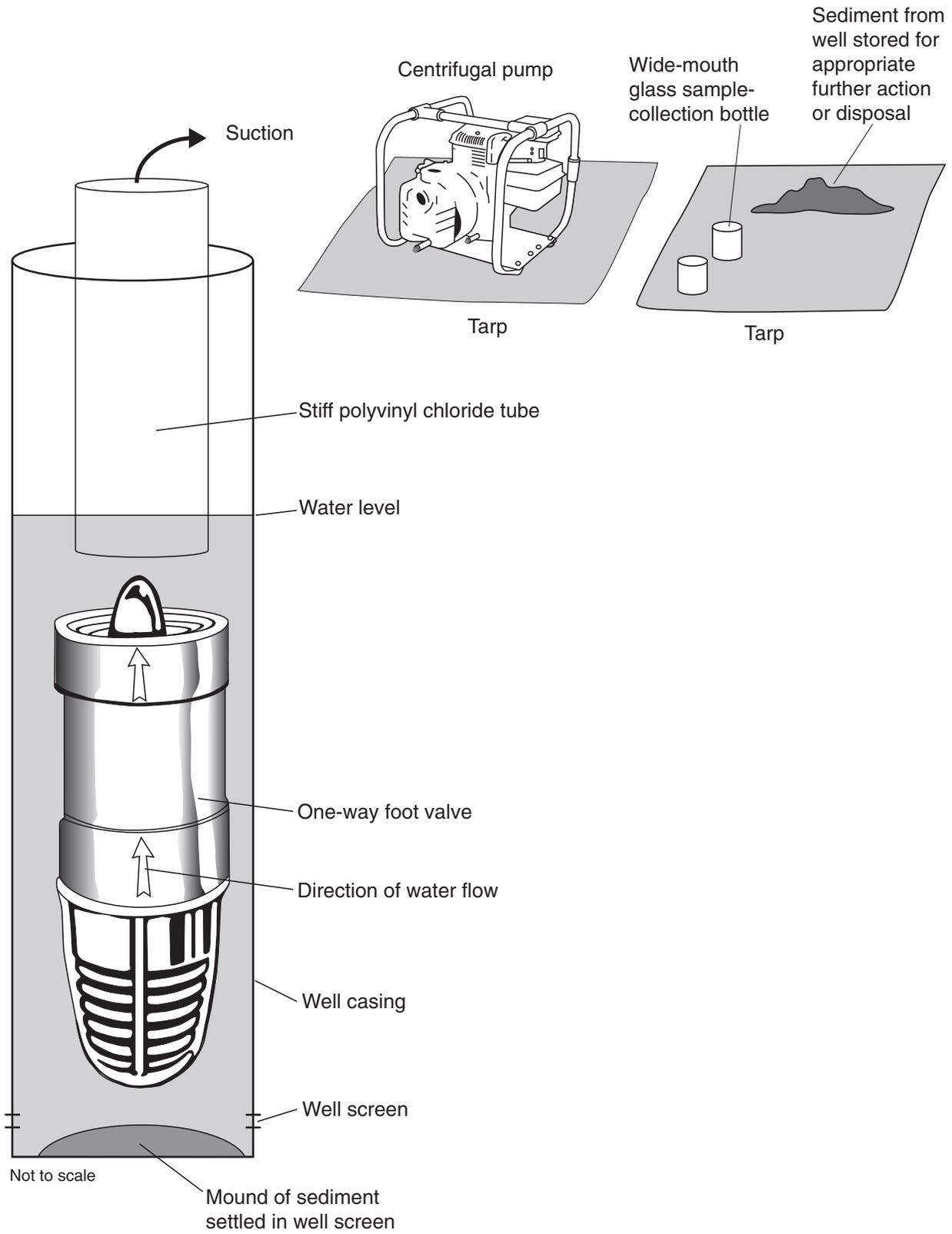


Figure 4. The device used to sample settled sediment in a well.

**Table 3.** Results of field monitoring of purge rate, drawdown, and turbidity that satisfied guidelines for low-flow sampling for selected wells at or near the BOMARC Missile Facility, Ocean County, New Jersey.

[BLS, below land surface; NTU, Nephelometric Turbidity Units; *italic* print where guideline was not satisfied; purge rate is the most frequently occurring value; data sorted in order of well depth; <, less than; negative drawdown indicates water-level rise]

U.S. Geological Survey well number	Sampling date (month/day/year)	Purge rate <sup>1</sup> (liters per minute)	Level of pump during purging (feet BLS)	Initial depth to water (feet BLS)	Depth to water at stable turbidity <sup>2</sup> (feet BLS)	Draw-down (feet)	Purging duration (minutes)	Number of casing volumes purged	Initial turbidity (NTU)	Maximum turbidity (NTU)	Final stable turbidity <sup>3</sup> (NTU)
291377	2/7/00	<i>7.16</i>	26.0	23.77	23.94	0.17	68	66.2	10.2	28.2	0.12
291370	2/11/00	.56	34.1	31.60	31.61	.01	63	5.7	12.5	12.5	0.38
291203	2/23/00	.29	40.0	38.76	39.07	.31	115	7.0	0.81	15.6	1.23
291379	1/6/00	.44	44.0	37.87	37.88	.01	65	3.5	185	185	1.14
291371	12/8/99	.36	44.0	39.05	39.05	0	245	11.7	83.4	83.4	2.76
291372	2/1/00	.49	45.8	44.33	44.28	-.05	63	4.2	1.25	1.39	.59
291375	12/3/99	1.15	50.0	47.67	47.70	.03	184	26.6	5.11	5.11	.32
291374	12/15/99	.45	60.0	53.35	53.33	-.02	63	4.4	4.46	4.50	.28
291376	2/15/00	.47	82.0	21.73	21.79	.06	81	.2	3.94	5.74	1.33
291378	8/25/99	.68	105.0	14.40	14.40	0	322	.9	30.8	40.4	<i>18.0</i>

<sup>1</sup> Guideline: Purge rate less than 0.5 liter per minute if possible (Puls and Barcelona, 1995).

<sup>2</sup> Guideline: Minimal drawdown (<0.5 feet) while pumping from the most productive interval (Puls and Barcelona, 1995).

<sup>3</sup> Guideline: Final stable turbidity that is less than 5 NTU if possible (Gibs and others, 2000).

## Well Sampling Procedures

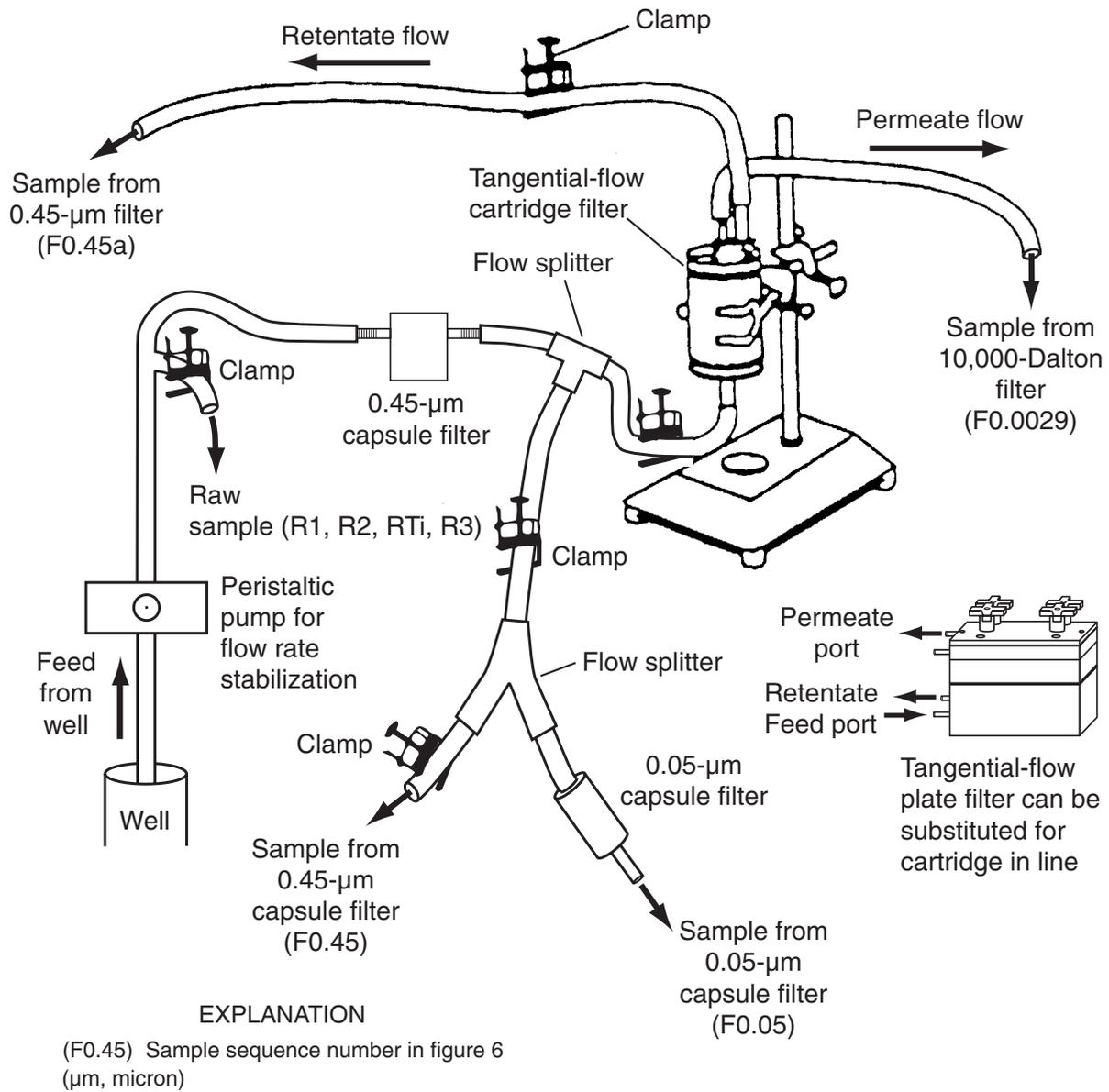
Stabilization and minimization of turbidity, as well as the absence of decline in the water level during low-flow purging, were considered the most important components in determining when to initiate sample collection (table 3). The low-flow purge rate used during sampling was that recommended in the low-flow purging technique of Puls and Barcelona (1995). The pumping rates for the observation wells ranged from 0.29 to 0.68 L/min (table 3). These rates were necessary for adequate flow through the sequential filters from which samples were ultimately collected. The submersible pump could not consistently maintain enough pressure to force flow through the filters at purge rates lower than the rates given above because of cavitation resulting from gas bubbles.

## Low-Flow Purge and Monitoring of Turbidity, Other Physical Characteristics, and Water Levels

The pumping rate, water level, and water turbidity were monitored as continuously as possible, beginning when the submersible pump was turned on. To maintain a consistent flow rate, a small peristaltic pump was placed in line with the discharge line from the submersible pump before the filtration assemblage (fig. 5). The peristaltic pump was calibrated in the laboratory and was set to the same pumping rate as the submers-

ible pump to maintain consistent positive pressure through the filter assemblage. The entire pumping scheme was established and maintained throughout well purging and sampling to avoid artifacts (artificially mobilized particles) resulting from changes in the pumping scheme.

Turbidity was monitored during well purging by use of a Hach 2100P Portable Turbidimeter; values were recorded every 2 minutes, if possible. Turbidity was used as a surrogate for particulate material that might be present in the sampled water. Unfiltered samples were collected throughout the purge period to determine changes in trace-element and radionuclide concentrations with changes in particle concentrations. Collection of filtered samples concurrently with unfiltered samples was delayed until turbidity stabilized. The stability-criteria concept used for this study was based on the published instrument analytical precision data as defined by Gibs and others (2000). The 2100P Portable Turbidimeter has a precision of  $\pm 0.4$  NTU at less than 20 NTU (Hach Inc., 1991). Turbidity was considered stable, and a water-quality sample was collected, when four consecutive readings 5 minutes apart did not vary by more than twice the instrumental precision of  $\pm 0.4$  NTU; that is, 0.8 NTU. On the basis of previous research, stable turbidity of less than 5 NTU was considered to be a representative value for the aquifer system, especially in the oxic environment encountered (Ryan and Gschwend, 1990; Gibs and others, 2000; and Ivahnenko and others, 2001).



**Figure 5.** Sample-splitting equipment for simultaneously collected filtered, tangential-flow ultrafiltered, and unfiltered samples.

The water level was measured two to four times with an accuracy of  $\pm 0.01$  ft by use of a weighted steel tape during the first 10 minutes after initiation of purging. The purging rate was reduced if drawdown was appreciable. An electric tape was lowered into the well with the sensor set about 0.5 ft below the water table. Cessation of the electric signal did not occur, indicating that drawdown had stabilized. The water level was measured about every 20 minutes thereafter with the weighted steel tape. Drawdown at the time of collection of the filtered samples was determined by measurement with the steel tape (table 3).

In addition to turbidity and water level, the field-determined properties pH, specific conductance, and water temperature were monitored as described by Wilde and Radtke (1999) but without use of a flow-through chamber. Measurements were made in a glass beaker that was continuously flushed with purge water. The concentration of dissolved oxygen was not monitored but was determined by Winkler Titration (iodometric with azide modification; Wilde and Radtke, 1999) at the time of stabilization of turbidity.

## Sample Type

A minimum of four types of water samples was collected from each observation well (fig. 6). The samples were collected in the following sequence. (1) A raw unfiltered sample was collected within the first minutes of pumping when turbidity was at or near the maximum. (2) A raw unfiltered sample was collected after turbidity stabilized. (3) A sample was filtered through a 0.45- $\mu\text{m}$  filter. (4) A sample was passed through a 0.45- $\mu\text{m}$  filter and a 0.0029- $\mu\text{m}$  (10,000 Dalton) filter in sequence (figs. 5 and 6). (The same sequence as for sample collection and equipment cleaning was maintained for the collection of equipment-blank samples, as detailed in figures 5, 6, and 7.) In some cases, a fifth sample was collected after the water passed through a 0.45- $\mu\text{m}$  filter and a 0.05- $\mu\text{m}$  filter, in sequence, to evaluate the presence of colloids ranging from 0.0029  $\mu\text{m}$  to 0.05  $\mu\text{m}$  in size. A minimum of two unfiltered samples per well also was collected for determination of suspended sediment concentration in addition to monitoring for turbidity. The first suspended sediment sample was collected concurrently with the initial unfiltered radionuclide sample. The second sample was collected immediately before the commencement of filtration. In cases where turbidity was high at the initiation of purging ( $>10$  NTU) but decreased rapidly or turbidity was extremely variable (changing by about 5 NTU per measurement), additional samples of unfiltered water were collected for determination of suspended sediment and radionuclide concentrations. Last, an unfiltered sample of water was collected from most wells after a minimum of one to two casing volumes of water were removed. From the radionuclide concentrations in these unfiltered samples, differences in contaminant concentrations in samples with different turbidities, and affinity with particles, could be determined. The final field-monitoring data for each well sampled, especially the initial, peak, and final stable turbidity when samples were collected, are listed in table 3.

Each sample bottle was labelled with the collection date and time and a predetermined sequence code which denoted the sequence status of the sample (filtered or not, and filter pore size, if applicable). The initial raw unfiltered sample (designated R1) was collected 1 to 3 minutes after initiation of well purging. This sample represents the concentration of constituents mobile in the raw water and constituents likely to sorb onto settled particulates at the bottom of the well casing and to be artificially mobilized by the initiation of well purging activity. The additional raw unfiltered samples that were collected while turbidity varied (designated R2 and RTi) provided an estimate in the variation of contaminant concentration with variation in particulate concentration. Unfiltered samples designated RTi, in general, were collected when the turbidity varied during purging by more than  $\pm 33$  percent in a 3-minute interval or increased by about 3–5 full NTU. The unfiltered sample at the time of turbidity stabilization (designated R3) is used to establish concentrations of contaminants mobile in the raw water, including those sorbed onto particulate material generated by, and mobile within, the aquifer matrix. Sequential filtering of

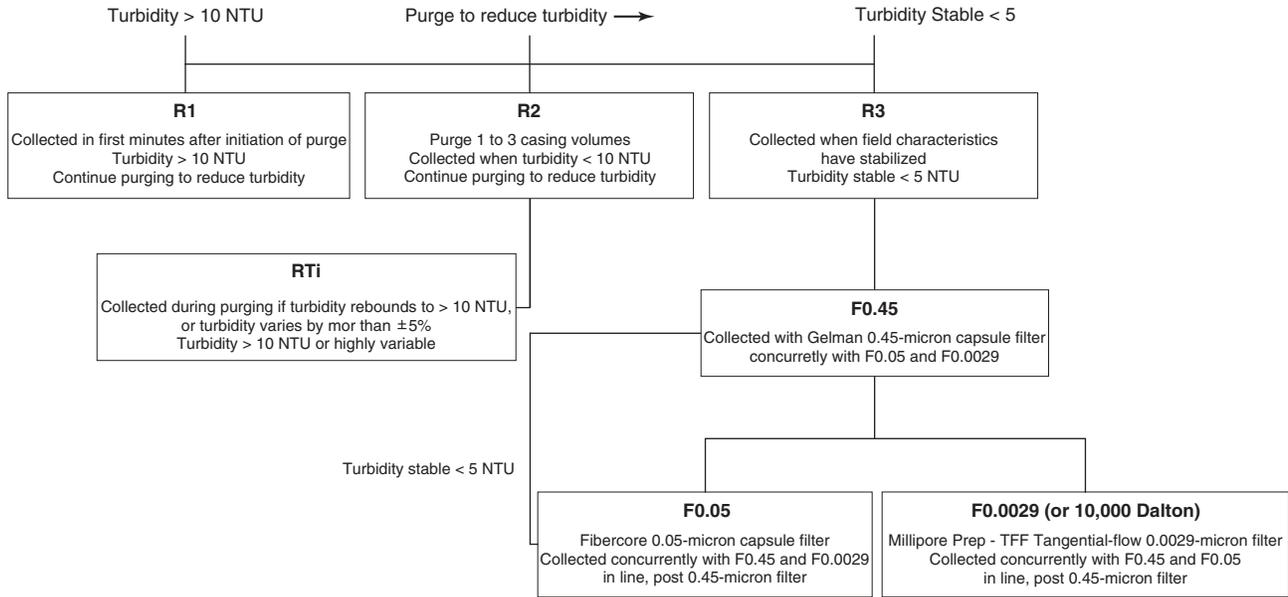
water through a 0.45- $\mu\text{m}$  filter and either a 0.05- $\mu\text{m}$  filter or a 0.0029- $\mu\text{m}$  filter provided a sample that contains concentrations of contaminants dissolved and sorbed to all colloids (designated F0.45), dissolved and sorbed to colloids less than 0.05  $\mu\text{m}$  in size (designated F0.05), and in the truly dissolved phase (molecules and molecular complexes less than 0.0029  $\mu\text{m}$  in size, designated F0.0029). The sample designations also are noted in figure 5 which details the actual sample-splitting design.

## Sample Collection with Filtration and Tangential-Flow Ultrafiltration

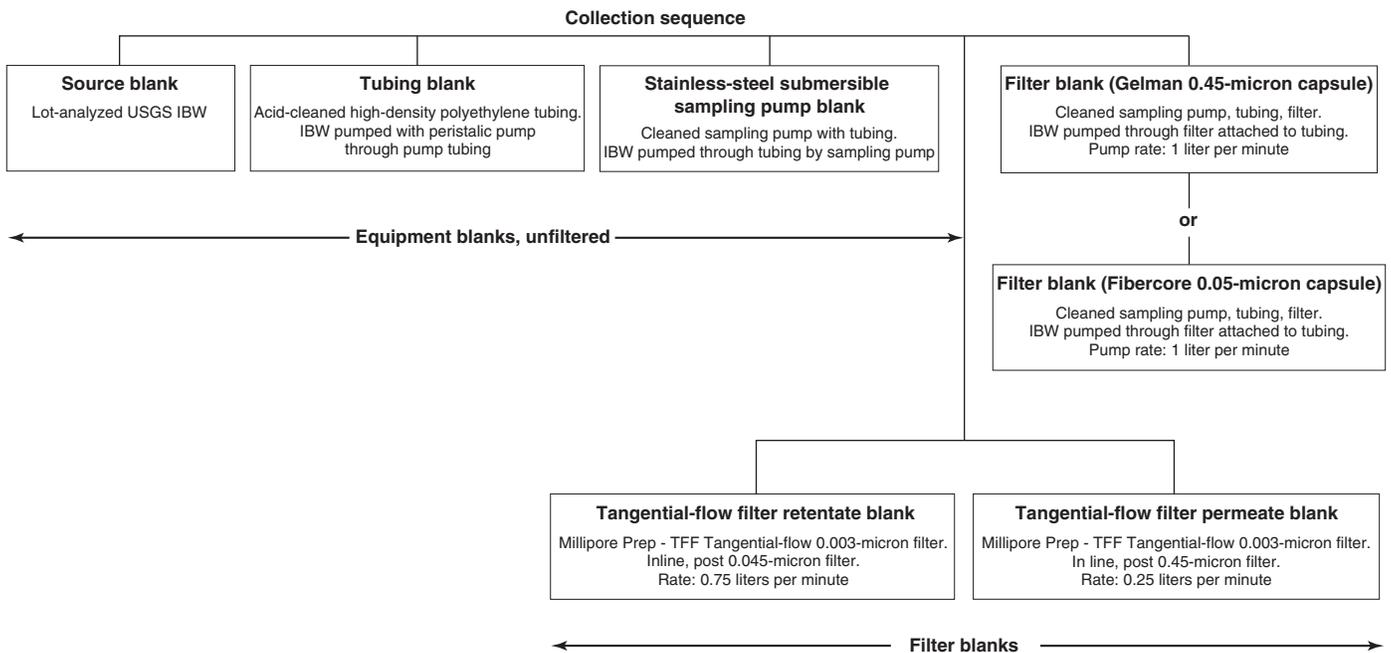
A diagram of the sampling apparatus used for unfiltered and filtered sample collection is shown in figure 5, and the filtration equipment used is listed in table 4. Tortuous-path, 0.45- $\mu\text{m}$  Gelman polyethersulfone capsule filters were used to filter particulates from raw water and provide the sample stream for the tangential-flow ultrafiltration system. A Millipore Prep/Scale-TFF tangential-flow ultrafiltration spiral-wound cartridge system was used to capture the colloidal phase and provide colloid-free water for collection of the truly dissolved phase.

The ultrafiltration cartridge system has three ports—the feed port, retentate port, and permeate port. The feed port is the input port. The feed port was connected to cleaned tubing in sequence after the 0.45- $\mu\text{m}$  capsule filters. The feed process consists of the water passing through the 0.45- $\mu\text{m}$  capsule filters. The ultrafiltration filter cartridge was mounted on a plastic bracket within the portable glove-bag chamber with the feed port pointed downward. The discharge or filtrate from the retentate port is the part of the sample that has flowed over the surface of the filter substrate, not through it. This part of the sample is the F0.45 (0.45- $\mu\text{m}$ ) sample collected from all well sites (fig. 5). The filtrate that flows from the permeate port is the F0.0029 (10,000 Dalton (0.003- $\mu\text{m}$ )) sample, or the truly dissolved phase, collected from all wells. For additional details and limitations regarding the use of tangential-flow ultrafilter as described here, see Szabo and others (2002). For additional information regarding the limitations of using these filters from an overall sampling perspective, see Babiarz and others (2000) and Hoffman and others (2000).

All ground-water samples were collected using rigorous “clean sampling” techniques and equipment cleaning (table 5) following procedures documented by Ivahnenko and others (1996; 2001) and Horowitz and others (1994). A strict sampling protocol was maintained in order to insure that sample handling and processing did not compromise sample integrity. All samples were collected as raw water drawn directly from the observation well by one of the dedicated small portable stainless-steel submersible pumps (fig. 5). The person collecting the sample wore powder-free latex gloves and did not handle any of the field monitoring or pumping equipment (Horowitz and others, 1994). PVC sample bottles were acid rinsed in the laboratory (table 4); before sample collection, additional rinsing was performed with deionized water (1L) and native purge water



**Figure 6.** Components of simultaneous tortuous-path and tangential-flow filtered sample collection consequent to collection of unfiltered samples and stabilization of turbidity.



**Figure 7.** Sequential collection of equipment-blank samples for quality assurance.

**Table 4.** Filtration equipment and sampling bottles used for field experiment sampling at or near the BOMARC Missile Facility, Ocean County, New Jersey.

Filters					
Pore size (micron)	Equipment <sup>1</sup>	Design	Surface area (square feet)	Quality assurance (per 10 samples)	Material
0.45	Gelman 12175	Tortuos-path capsule	0.79	2 blanks	Polyethersulfone
0.05	Fibercor Fiber-Flo 50	Pleated fiber cartridge	0.6	1 blank	Polysulfone
0.0029	Millipore Prep/Scale-TFF	Tangential- flow spiral wound cartridge	0.9	2 blanks	Polyethersulfone
0.0029	Millipore Minitan-S	Tangential- flow filter plate	0.056	1 blank	Polysulfone
Sampling bottles					
Type			Quality assurance		Sample type
High-density polyethylene, acid washed, 1 liter			None (internal quality assurance)		Filtered trace elements, radionuclides
Glass, wide-mouth			None		Suspended sediment
Glass, cuvettes, 25 milliliters			Day blanks (10 total)		Turbidity
Tubing, preservatives					
Type			Quality assurance		Sample type
High-density polyethylene tubing			2 blanks associated with pump; tubing acid-washed for trace elements, deionized water rinsed for radionuclides		All pumped samples
Nitric acid, Ultrex, in high-density polyethylene container			Used in all blanks; each lot, internal quality assurance analyses		Trace elements, radionuclides
Reagent grade lot analyzed hydrochloric acid			Lot analysis; used only to acid wash tubing fittings and tubing		Trace elements

<sup>4</sup> The use of brand names is for identification purposes only and does not constitute endorsement by the U.S. Government.

(0.25L). Reduction of sample exposure to wind-blown aerosol particles was accomplished with a portable enclosed sample-collection chamber. Some samples were not collected within the confines of the designated dedicated clean sampling van as recommended by Ivahnenko and others (1996), however, because of concern over the accumulation of organic vapors within the clean sampling van from the water sample. Dust and aerosol control was maintained in the vicinity of the sample by enclosure within portable glove-bag chambers on a small portable table and the use of a disposable heavy tarp on the ground in the sample-collection area. Ultra-pure nitric acid was used to preserve samples to be analyzed for trace elements and radionuclides (table 4). The acid was added to the bottles in a separate preservation glove-bag chamber (Horowitz and others, 1994) after sample collection. This process, which required the reopening of the sample bottle for brief moments of time, was always accomplished inside the dedicated clean sampling van (Ivahnenko and others, 1996).

## Safety Considerations

Because of the possible presence of mixed inorganic and organic wastes at the observation-well sites, the team safety officer initially checked the headspace in the well to be sampled for organic vapors, then both the initial discharge water and the ongoing purge water, with a portable photo-ionization detector (H-nu Systems Model PI-101; 10.2 eV lamp). During sampling, an individual checked the air quality near the portable glove bag as well as the breathing zone of the sampler. When organic vapors were detected near the portable glove bag or in the breathing zone of the sampler, sampling proceeded only after engineering solutions to remove organic vapors were put in place: the van door was opened, the ceiling fan was turned on, and a window fan was set up to exhaust the air in the van. If these steps did not resolve the problem of detectable vapor buildup inside the sampling area (partially enclosed van) or were too obtrusive for the sampler, the portable sampling glove

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**Table 5.** Laboratory cleaning process for filtration, pumping, and sampling equipment used for the low-level ground-water trace-element sampling protocol of Ivahnenko and others (1996) or established during the field experiment at or near the BOMARC Missile Facility, Ocean County, New Jersey.

[DIW, deionized water; HCl, hydrochloric acid; %, percent; NA, not applicable]

Equipment	Cleaning steps	Solution	Volume (liters)	Rate (liters/minute)	Time (minutes)	Flow control
Ultra-filter	Preservative solution; drained	Ammonia-based preservative <sup>1</sup>	NA	NA	NA	NA
	Initial rinse	Sterile DIW	2	1.0	NA	Retentate clamp open
	Permeate	Sterile DIW	4	.5	NA	Retentate clamp
	Retentate	Sterile DIW	1	1.0	NA	Retentate clamp open
Capsule filter	Initial rinse	Sterile DIW	.25	.5	NA	NA
Pump	Disassemble pump; rinse out lubrication reservoir	Sterile DIW	As needed	NA	NA	NA
	Scrub impellers	0.1% Liquinox solution	As needed	NA	NA	NA
	Wash	Recycled 0.1% liquinox solution	4	4.0	25	Pump rate
	Flush	Recycled sterile DIW	4	4.0	10, repeat 2 times	Pump rate
	Flush	Sterile DIW	4	1.0	NA	Pump rate
Tubing	Flush	Recycled sterile DIW	8	1.0	15, repeat	NA
	Flush	Sterile DIW	As needed	1.0	10	NA
Fittings	Sonicator bath	0.1% liquinox solution	5	NA	5	NA
	Sonicator bath	Sterile DIW	5	NA	5, repeat	NA
	Acid rinse, freshly made	5% reagent grade HCL	As needed	NA	60	NA
	Flush	Sterile DIW	As needed	1.0	5	NA

<sup>5</sup> alkyl- benzyl- dimethyl ammonia chloride.

bags were moved outside onto a tarp-covered area to complete sampling. Although this process is a slight departure from the technique of Ivahnenko and others (1996), the use of heavy tarp on the ground and the portable glove-bag chambers minimized or eliminated the risk to the sampling team and at the same time did result in preservation of sample integrity.

A portable scintillometer with an alpha-particle sensitive probe (Ludlum 2221) was used to check the outer protective field garments (disposable Tyvex and rubber boots) of the sampling team for contamination with alpha-particle emitting radioisotopes such as Pu and Am. Because alpha particles are strongly attenuated even by air (Knoll, 1989), the detector was placed as close as possible to the surface of the garment being monitored. The outer protective field garments of the sampling team were scanned for contamination on an occasional basis during field operations to insure that personnel were not contaminated with "hot particles," a matter of concern for safety and for preservation of sample integrity by avoiding accidental contamination with "hot particles" during sample handling. A

final probe scan was done before departure from each site to insure radioactive "hot particles" were not transported away from the site. Although a portable gamma ray detection device may be more readily available and will detect the presence of Am (Ibrahim and others, 1995), the response from such a device may be difficult to interpret in typical field areas because of the background gamma emissions from potassium in naturally occurring clay particles. Individual whole-body radiation dose was monitored by radiation badges worn at chest height.

### Techniques of Quality Assurance

For quality control and to determine any variability in constituent concentrations caused by varying amounts of particulate matter during sampling, many replicate samples were collected from each well. In most cases, a complete sequential replicate sampling of the entire initial and final unfiltered sampling was performed (8 of 10 sites); the filtered sequence of samples was replicated less frequently (3 of 10

sites) because of the time-consuming nature of tangential-flow ultrafiltration. Laboratory duplicate analysis of randomly selected samples also was provided by the analytical laboratory. At least one sample was randomly selected for duplicate analysis from 7 of the 10 sites. To determine the amounts of trace-element contamination introduced during the sampling process, equipment and process blank samples were collected (Ivahnenco and others, 2001) and analyzed for trace elements (indicative of contamination during sample handling and processing), as well as the radionuclides of interest. Inorganic blank water (IBW), certified by the USGS, was passed through field equipment in the laboratory; filtered and unfiltered samples of the IBW were collected using the same procedures used for ground-water samples (fig. 7).

For the ground-water trace-element sampling techniques used, cleaning of the pump between each sample collection was required (table 5). This cleaning is necessary to avoid possible cross-contamination among samples. The stainless-steel submersible pump was cleaned with a soap solution, rinsed with tap water, then rinsed with DIW before use. Acid rinse is not used in the pump cleaning process because it would etch the stainless-steel surfaces on the submersible pump (Wilde and others, 1998; Ivahnenco and others, 2001). Etched surfaces increase the rate of leaching of trace elements from stainless steel (chromium, iron, manganese, molybdenum, and nickel), which could contaminate samples (Wilde and others, 1998). The pump was stored in disposable plastic bags after air drying. The cleaning procedures for the single-use disposable high-density polyethylene tubing and PVC tube fittings were similar to the pump cleaning procedures, but a dilute hydrochloric acid (HCl) rinse was used; the procedures are described in detail by Horowitz and others (1994) and Ivahnenco and others (1996). The sample tubing was discarded immediately after use. The cleaning techniques have produced acceptable results as determined on the basis of analyses of trace-element-free blanks collected from the tubing and the pump (Ivahnenco and others, 1996; 2001).

## Laboratory Analysis for Radionuclides

Concentrations and activities of radionuclides were determined by use of standard methods approved by the U.S. Environmental Protection Agency and USGS (Krieger and Whitaker, 1980; Thatcher and others, 1977). Gross radioactivity of ground-water samples was measured as gross alpha-particle activity and gross beta-particle activity. The specific isotopes of radionuclides analyzed for in water from all wells are Pu-238 and 239+240; Am-241; and U-238, -234, and -235. Concentrations of these same isotopes were analyzed for in the settled-sediment samples recovered from the bottoms of the observation wells. Isotopes of Th-228, -230, and -232 were analyzed for in water samples from 5 of the 10 wells.

All radiochemical samples were analyzed by Severn Trent Laboratories in Richland, Washington. Personnel at the USGS National Water Quality Laboratory (NWQL) reviewed all internal laboratory quality-assurance data from standards,

blanks, and laboratory splits, and had the authority to order the reanalysis of any batch of samples if quality-assurance guidelines were not met. Samples were reanalyzed when initial results were considered questionable because of lack of precision for duplicates, high background radiation, or other analytical problems related to instrument operating conditions.

## Detection Methods

Concentrations of isotopes of Pu within the water samples were determined by alpha spectrometry, the most commonly used technique to determine concentrations of Pu isotopes. The Pu is first separated and purified. Pu-242 is added before sample preparation to provide determination of chemical yield (Sill and others, 1979). The evaporated residue from the water samples is dissolved in nitric acid ( $\text{HNO}_3$ ) and heated. The Pu oxidation state is adjusted to the +4 valence with sodium nitrite. The Pu is then separated from major and many trace elements by adsorption onto an anion-exchange column (BioRad AG 1-X8 50–100 mesh resin). After the interfering elements, such as U, Th, and Am, are separated with  $\text{HNO}_3$  and HCl washes, Pu is desorbed from the resin by washing with ammonium iodide solution in HCl. The Pu is concentrated further and residual iodine from the elution is eliminated by adding  $\text{HNO}_3$  and evaporating the solution to dryness. The Pu is electroplated onto stainless-steel disks. The isotopic concentrations are then measured by alpha spectrometry. The Pu-238 (alpha particle energy, 5.50 MeV (million electron volts)) concentration can be distinguished from that of Pu-239 and Pu-240 and is reported as the concentration of this single isotope. Pu-239 cannot be differentiated from Pu-240 by alpha spectrometry, however, because the energy of the emitted alpha particles is nearly identical (5.15 and 5.16 MeV, respectively). The concentrations of Pu-239 and Pu-240 are reported as the concentration of Pu-239 plus Pu-240 (Pu-239+240). The thermal ionization mass spectrometry technique (TIMS) must be used in order to distinguish the concentration of Pu-239 from that of Pu-240 (Liator, 1999), but it was not used for this study. A final complication in the analysis of the alpha-particle emitting Pu radionuclides is that naturally occurring Th-228 emits alpha particles with energies of 5.42 MeV; hence, even if the greatest care is taken to distinguish the Th-228 from Pu-238, interference, overlap, or misidentification of the isotopes is possible when using the alpha-spectrometry technique. In addition, Pu-241 undergoes beta decay and, thus, cannot be detected with alpha spectrometry. Pu-241 decays to Am-241 but has a relatively short half-life (14.4 years), which makes it hard to detect in the environment 15–20 years after dispersal (low concentrations as a result of rapid decay).

Isotopic concentrations of U and Th and concentrations of Am-241 were determined by alpha spectrometry after individual pre-concentration, separation, and purification procedures. In general, the most important step is the actual separation procedure using anion-exchange resins (BioRad AG 1-X4 and 1-X8) to capture, then elute, the target radionuclide. The U and

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Am-241 were eluted with 8 M (molar)  $\text{HNO}_3$ , whereas Th was eluted with 8 M HCl from the anion exchange column. The U is further purified by extraction from a second anion-exchange column with methyl isobutyl ketone. Oxalate co-precipitation was used to pre-concentrate Am-241. Am-241 then required further purification and separation by placement on an additional anion-exchange column (BioRad AG 1-X4 100–200 mesh) and elution with an alcohol solution. (Am-241 also can be determined by gamma spectroscopy (Hulse and others, 1999), but alpha-spectroscopy is preferable for low concentrations because the background radiation noise is less than that for gamma spectroscopy. Therefore, the gamma spectroscopic technique is used mostly for quick surveys in the field where high concentrations are suspected (Ibrahim and others, 1995).

Gross alpha-particle activity and gross beta-particle activity were determined by counting in a low-background gas proportional alpha-beta-particle counter for 100 minutes. The samples were first evaporated to dryness; the residues then were deposited on a stainless-steel planchet and dried in a desiccator. Residues were weighed before counting to ensure that the mass did not impair counting efficiency. For particle-laden or mineralized water samples, excessive sample mass could considerably attenuate radiation emission, resulting in poor precision (non-reproducibility) and possible high or low bias. Calibrations for the counter were made with Th-230 standards for gross alpha-particle activity and with cesium-137 (Cs-137) standards for gross beta-particle activity (Krieger and Whittaker, 1980).

### Reporting of Analytical Results for Radionuclides

The raw, unrounded values for all radionuclide concentrations in picocuries per liter (pCi/L) are reported by the laboratory. The laboratory also reports the precision estimate (P.E.), which is another term for measurement uncertainty and measurement error, computed at two standard deviations about the count value (labeled 2-Sigma P.E.). The 2-Sigma P.E. is provided by the laboratory for each analysis because the rate of radioactive decay varies at any instant in time even though the long-term decay rate is stable. All measurements of radioactivity are associated with a degree of uncertainty in the measurement, which is also known as the counting uncertainty. Other laboratory sources of measurement uncertainty and error are added to the counting uncertainty. The degree of uncertainty of the radioactivity measurement is the confidence interval expressed as two standard deviations; that is, 95 of 100 measurements of radioactivity of the sample would fall in the range denoted by the reported radioactivity, plus or minus the 2-sigma P.E. (precision estimate, composite of laboratory error, and counting uncertainty).

Finally, the sample-specific minimum detectable concentration (SSMDC) determined by the laboratory for each sample is reported. Instruments that count radioactivity record both the radioactivity of the water sample and the background radioactivity during the time the sample is being measured. Quantifying small amounts of radiation in a given sample is difficult

because the analytical instruments record the background radiation during their operation. The radiation emitted from the radionuclide being quantified must be clearly distinguishable above the instrumental background radiation. The minimum quantity of a specific radionuclide detected by the counting instrument for any given analysis with the unique instrument operating conditions and background radiation is defined as the minimum detectable concentration (MDC) (Strom and MacLellan, 2001). In general, MDC is further defined by the requirement that the counted radioactivity must differ from the background count by 6 times the standard deviation of the background count or twice the critical level where the likelihood of a false positive is 5 percent or less (Currie, 1968). This value is computed individually for each radionuclide analysis on the basis of the instrument operating conditions at the time of analysis; the SSMDC is reported for each analysis for each isotopic constituent. The laboratory reporting level (LRL) is defined as the minimum quantity of a specific radionuclide that can be quantified routinely and reliably with general instrument operating conditions. The LRL is a target value for detection capability already known prior to analysis and readily achievable with routine operating conditions. The LRL is typically at least a factor of 2 to 3 times the SSMDC for laboratory blanks (results for which vary with background radioactivity). The LRL target was 0.1 pCi/L for all the radionuclides in this study, and the reported values of the SSMDCs indicate measurement performance was satisfactory. The LRL can be changed when changes occur in instrumentation, radiation background, typical counting times, routine sample volumes, the long-term average of individual analysis SSMDCs, and other factors. These analytical terms are described in detail in the Glossary at the back of the report.

### Analysis of Shallow Ground Water and Settled Sediment

The raw, unrounded radiochemical analytical data for constituent concentrations in water as reported by the laboratory and values for the characteristics turbidity, water level, water temperature, specific conductance, and pH, which were continuously monitored in the field during sampling, are presented in this section. Results of analyses for radionuclides in equipment-blank samples are provided in table 6. Results of radiochemical analysis are provided for about 90 samples from 10 observation wells in table 7A (back of report). The laboratory-reported 2-Sigma P.E. and the laboratory reported SSMDC for each individual sample are listed in tables 6 to 8. The depth of the open interval for each well is provided in table 1, and the depth of the pump setting within the well is provided in table 3. The “sample-type” column in table 7A and 7B (back of report) lists whether the sample is the raw, unfiltered, or a type of filtered sample. A detailed explanation of the sample types and how they were collected is provided in the section “Sample Type.” Data for each well are presented in

**Table 6.** Concentrations of radionuclides in equipment blanks used for the field experiment sampling protocol at or near the BOMARC Missile Facility, Ocean County, New Jersey.

[10K ultrafilter, 10,000 Dalton tangential-flow ultrafilter cartridge; µg/L, microgram per liter; pCi/L, picocuries per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; <, less than; --, no data; number in parenthesis is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number. Equipment blanks collected 8/26/99 at well 29-1378 and at well 29-1203 on 2/17/00 and 3/17/00 and 3/15/00]

Blank type	Sample number	Date (month/day/year)	Time	Uranium, total (µg/L) (22703)	Plutonium-238 (pCi/L) (22001)	Plutonium-238, 2SIGMA P.E. (pCi/L) (49939)	Plutonium-238, SS MDC (pCi/L)	Plutonium-239+240, (pCi/L) (49940)	Plutonium-239+240, 2SIGMA P.E. (pCi/L) (49941)	Plutonium-239+240, SS MDC (pCi/L)	Americium-241 (pCi/L) (29867)	Americium-241, 2SIGMA P.E. (pCi/L) (49942)	Americium-241, SSMDC (pCi/L)
Pump, unfiltered	99900169	8/26/99	1450	--	-0.000572	0.00115	0.00808	-0.000572	0.00115	0.00808	0.00375	0.00534	0.00508
Deionized water source unfiltered	00000351	2/17/00	1550	--	--	--	--	--	--	--	.00203	.00408	.00551
Retentate flow (10K ultrafilter)	00000074	2/17/00	1551	<.2	--	--	--	--	--	--	.00237	.00475	.00642
Permeate flow (10K ultrafilter)	00000075	2/17/00	1552	<.2	0	.00351	.00388	-0.000572	.00115	.00809	.000335	.00385	.01150
0.45 Filter	00000098	2/17/00	1553	<.2	-0.000854	.00365	.0122	.000284	.00577	.01490	.00328	.00468	.00445
0.45 Filter, concurrent split	00000352	2/17/00	1553	--	.000404	.00492	.0158	--	--	--	.00372	.00530	.00505
0.05 Filter	00000076	2/17/00	1555	<.2	-0.000586	.00118	.00828	.00293	.00416	.00397	--	--	--
Reused retentate flow (10K ultrafilter)	00000077	3/15/00	1353	<.2	--	--	--	--	--	--	--	--	--
Reused permeate flow (10K ultrafilter)	00000078	3/15/00	1354	<.2	--	--	--	--	--	--	--	--	--

Blank type	Date (month/day/year)	Time	Uranium-238 (pCi/L) (22603)	Uranium-238, 2SIGMA P.E. (pCi/L) (75991)	Uranium-238, SSMDC (pCi/L)	Uranium-234 (pCi/L) (22610)	Uranium-234, 2SIGMA P.E. (pCi/L) (75992)	Uranium-234 SSMDC (pCi/L)	Uranium-235 (pCi/L) (22620)	Uranium-235, 2SIGMA P.E. (pCi/L) (75994)	Uranium-235, SSMDC (pCi/L)	
Pump, unfiltered	99900169	8/26/99	1450	-0.00253	0.00256	0.0217	0.0108	0.00147	0.0272	-0.00127	0.00716	0.0260

Blank type	Date (month/day/year)	Time	Thorium-232 (pCi/L) (75976)	Thorium-232, 2SIGMA P.E. (pCi/L) (75999)	Thorium-232, SSMDC (pCi/L)	Thorium-230 (pCi/L) (26503)	Thorium-230, 2SIGMA P.E. (pCi/L) (75997)	Thorium-230 SSMDC (pCi/L) (61738)	Thorium-228 (pCi/L) (61739)	Thorium-228, 2SIGMA P.E. (pCi/L)	Thorium-228, SSMDC (pCi/L)	
Pump, unfiltered	99900169	8/26/99	1450	0.00467	0.012	0.028	-0.00351	0.00414	0.0369	-0.017	0.017	0.0741

**Table 8.** Concentrations of radionuclides in sediment samples from the bottom of selected observation wells at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999.

[Data sorted by well depth. pCi/g, picocuries per gram; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number]

U.S. Geological Survey well number	Date (month/day/year)	Begin time	Plutonium-238 (pCi/g) (49974)	Plutonium-238, 2SIGMA P.E. (pCi/g) (49975)	Plutonium-238, SSMDC (pCi/g)	Plutonium-239+240 (pCi/g) (49976)	Plutonium-239+240, 2SIGMA P.E. (pCi/g) (49977)	Plutonium-239+240, SSMDC (pCi/g)	Americium-241 (pCi/g) (49980)	Americium-241, 2SIGMA P.E. (pCi/g) (49981)	Americium-241, SSMDC (pCi/g)	Uranium-238 (pCi/g) (75940)
291377	10/25/1999	1025	-0.000471	0.000945	0.0237	0	0.0143	0.0159	-0.000367	0.000737	0.0185	0.0992
291370	11/5/1999	1200	.00385	.00842	.0169	-.000668	.000951	.0191	0	.00704	.00779	.252
291203	10/25/1999	1200	0	.0286	.0316	.0214	.0332	.0531	.00382	.00768	.0104	.0351
291203	10/25/1999	1201	0	.0153	.0169	0	.0153	.0169	.00377	.00758	.0102	.00336
291379	10/22/1999	1200	.00575	.0115	.0156	.0163	.0201	.0262	.00421	.00845	.0114	.112
291379	10/22/1999	1201	-.000329	.00066	.0165	0	.01	.0111	.00795	.0123	.0197	.123
291379	10/22/1999	1201	.00422	.00924	.0185	.00458	.00918	.0124	-.000316	.000635	.0159	.068
291379	10/22/1999	1201	0	.00946	.0105	-.000617	.000878	.0176				
291371	10/26/1999	1410	-.000585	.00117	.0294	.0073	.0147	.0198	-.000277	.000556	.0139	.0309
291371	10/26/1999	1411	.00512	.0136	.0336	.00619	.0136	.0271	0	.00952	.0105	.0165
291371	10/26/1999	1411	0	.025	.0276	0	.025	.0276	.00698	.0108	.0173	.0441
291372	10/18/1999	1335	Samples spilled at laboratory			--	--	--	--	--	--	--
291375	10/21/1999	1000	0	.0212	.0234	-.00138	.00197	.0394	0	.0111	.0122	.0278
291374	10/21/1999	1200	0	.0134	.0148	0	.0133	.0148	0	.0101	.0112	.0709
291376	10/27/1999	1200	0	.0148	.0163	.00	.0147	.0163	0	.0108	.0119	.217
291376	10/27/1999	1201	-.000448	.000899	.0225	.00	.0136	.0151	.00865	.0129	.0181	.214

**Table 8.** Concentrations of radionuclides in sediment samples from the bottom of selected observation wells at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999.—Continued

U.S. Geological Survey well number	Uranium-238, 2SIGMA P.E. (pCi/g) (04113)	Uranium-238, SSMDC (pCi/g)	Uranium-234 (pCi/g) (75942)	Uranium-234, 2SIGMA P.E. (pCi/g) (04111)	Uranium-234, SSMDC (pCi/g)	Uranium-235 (pCi/g) (75975)	Uranium-235, 2SIGMA P.E. (pCi/g) (75947)	Uranium-235, SSMDC (pCi/g)
291377	0.0488	0.025	0.106	0.0514	0.0345	0.00341	0.0102	0.0268
291370	.0798	.0112	.173	.0625	.0188	.00412	.00828	.0112
291203	.0286	.028	.0216	.024	.0371	-.0042	.00278	.0361
291203	.00736	.0147	.00366	.00734	.00991	.00	.00895	.00991
291379	.0454	.00982	.0828	.038	.0166	.00667	.0104	.0166
291379	.0584	.0283	.118	.0568	.0283	.0166	.0199	.0228
291379	.0346	.0153	.0455	.0276	.0103	.00	.0093	.0103
291379								
291371	.0204	.00839	.0217	.0168	.00839	.00	.00758	.00839
291371	.015	.00893	.0362	.0228	.00893	.00659	.00939	.00893
291371	.0269	.0149	.037	.0244	.01	.00739	.0105	.01
291372	Samples spilled at laboratory			--	--	--	--	--
291375	.0263	.0263	.0149	.0202	.0325	.00919	.0165	.0325
291374	.0369	.0113	.0292	.0227	.0113	-.000334	.000671	.0168
291376	.0683	.016	.2	.0646	.00951	.0102	.0123	.0141
291376	.0679	.00964	.16	.0562	.00964	.00712	.0102	.00964

order by date and time of day the sample was collected. Replicate, triplicate, and laboratory duplicate samples also are listed among the specific raw unfiltered and filtered samples in order by the time the sample was collected in table 7B. Results of analyses for radionuclides in bottom sediment are given in table 8.

### Quality-Assurance Evaluation of Laboratory Results for Equipment Blanks

The absence of detectable radionuclides of concern in the equipment-blank sample before or after filtration (table 6) indicates that the samples are not contaminated with low concentrations of radionuclides by the pumping equipment, filter material, or field or laboratory sample handling. This result verifies the adequacy of the care taken on site to avoid exposure of samples, sampling equipment, and personnel to radioactive "hot particles" possibly present in soil and of the extensive cleaning of pumping equipment using the protocols of Ivahnenko and others (2001) and Wilde and others (1998) to avoid sample cross-contamination. Contamination in the laboratory or excessive background radiation is not indicated by results of analyses of blank waters.

Manganese, cobalt, and zinc were detected in at least one equipment blank sample; other trace elements were not detected in any equipment blank samples. (See Szabo and others, 2002, table 6.) Manganese was detected in IBW that passed through the portable stainless-steel pump but not in IBW that passed through the pump and one of the filters. Detection of manganese in blank samples collected unfiltered from the stainless-steel pump is consistent with the results of Ivahnenko and others (2001) and indicates minor contamination from corrosion of the stainless steel. The filters, in general, do not add to the low-level trace-element contamination introduced by the portable stainless-steel pump. Internal quality assurance, analysis of standards, and examination of control charts at the laboratory resulted in identification of occasional and random high bias for cobalt in late 2000 (Connor and others, 2001); the information was not available to Szabo and others (2002) before publication of their report.

### Turbidity

In general, turbidity decreased by an order of magnitude or more during the first 10 to 15 minutes of well purging (fig. 8). Turbidity was high initially, increased in some cases during the first 2 to 3 minutes of pumping until a peak value was reached, then decreased quickly at first, then more gradually. For most wells, turbidity continued to decrease gradually for 60 to 120 minutes until a steady-state value of less than 1 NTU was reached (fig. 8). As the steady state was approached, the minute-to-minute variability in turbidity decreased to less than  $\pm 10$  percent, and variability, even over a 5- to 10-minute interval, was generally within  $\pm 40$  percent. Typically, a minimum of

60 minutes of well purging was required before a steady state was achieved with no more than  $\pm 0.8$  NTU variability in turbidity of less than 5 NTU for four consecutive readings, 5 minutes apart. These results are consistent with those of Ivahnenko and others (2001), who also report a minimum of 60 minutes of well purging before steady-state values of turbidity were achieved. For a number of wells (4 of 10; wells 29-1371, 29-1375, 29-1377, and 29-1379), turbidity varied by about an order of magnitude over random spans of 10 to 15 minutes during purging (fig. 8) and did not stabilize until 120 minutes or more of purging. Turbidity for two of the wells (wells 29-1203 and 29-1375) did not stabilize even after 240 minutes of purging. It is possible that the slight variation in pumping rate was a reason that the turbidity did not stabilize. These wells were sampled after about 240 minutes or more, using a relaxed standard that required turbidity to vary by less than  $\pm 25$  percent within a 10-minute period. Turbidity remained greater than 15 NTU even after 420 minutes of purging for well 29-1378.

Initial particle concentrations and variations in particle concentrations were highest among sample sets with the highest turbidity (table 7). Because Pu is known to be transported as colloidal particles (Penrose and others, 1990; Harnish and others, 1995), variation in particle concentrations is a concern; therefore, a summary of additional investigations regarding particle concentrations in ground water at this and other sites is provided.

Concentrations of particles in the water at the Facility determined by settling correlate strongly with turbidity (Szabo and others, 2002, fig. 10), but the high LRL (1 mg/L) makes the technique applicable only to turbid water (turbidity  $\geq 5$  NTU). Provisional particle concentrations in water samples determined with the light scattering technique (Szabo and others, 2002, fig. 9) also correlate strongly with turbidity, but the sensitivity of this technique to particle size and shape makes the technique easily applicable only to non-turbid water (turbidity  $\leq 3$  NTU). The apparent trend lines shown by Szabo and others (2002, figs. 9 and 10) of particle concentration as a function of turbidity indicate that a low concentration (less than the LRL of both the settling and light scattering techniques) of particles can be present in the samples even with low, stable turbidity. The longest purge time in this field experiment was nearly 6 hours; the possibility that particle concentrations may be reduced with purging for more than 6 hours was not investigated. Results of this investigation reaffirm that in the oxic environments encountered, low particle (low colloid) concentrations (thus, low turbidity) with a few exceptions could be the norm in the aquifer system itself; the nature of long-term variability could not be readily determined with available instrumentation.

Particle concentrations and turbidities determined in this study of the Kirkwood-Cohansey aquifer system are similar ( $< 1$  mg/L and  $< 1$  NTU, respectively) to those noted by Ryan and Gschwend (1990) in similarly oxidizing environments in this same aquifer system after considerable purging. The turbidity and particle concentrations are consistent with most of the colloid-concentration data reported for other sites by Backhus and others (1993). The results for turbidity over time

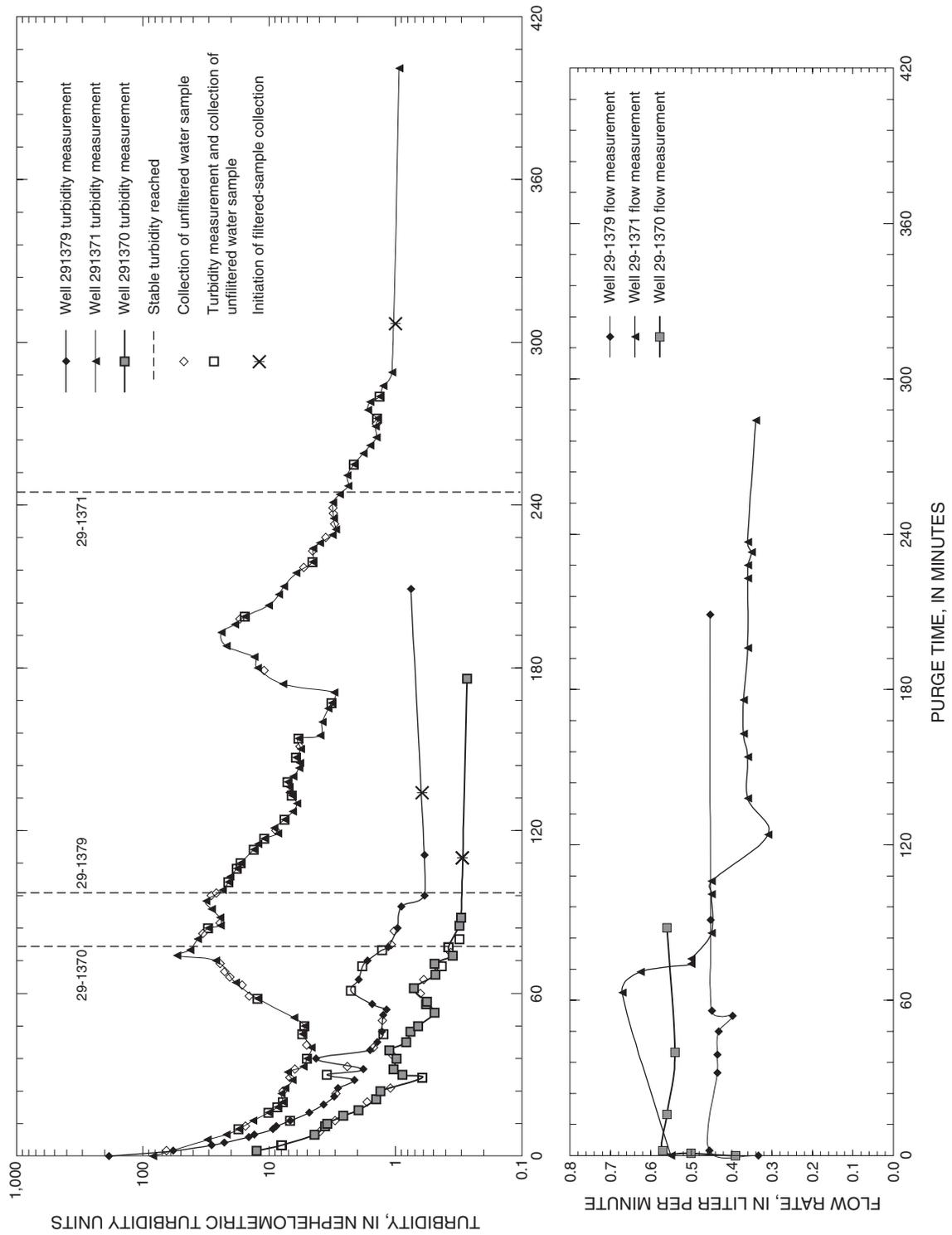


Figure 8. Turbidity and purging rate for the observation wells at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.

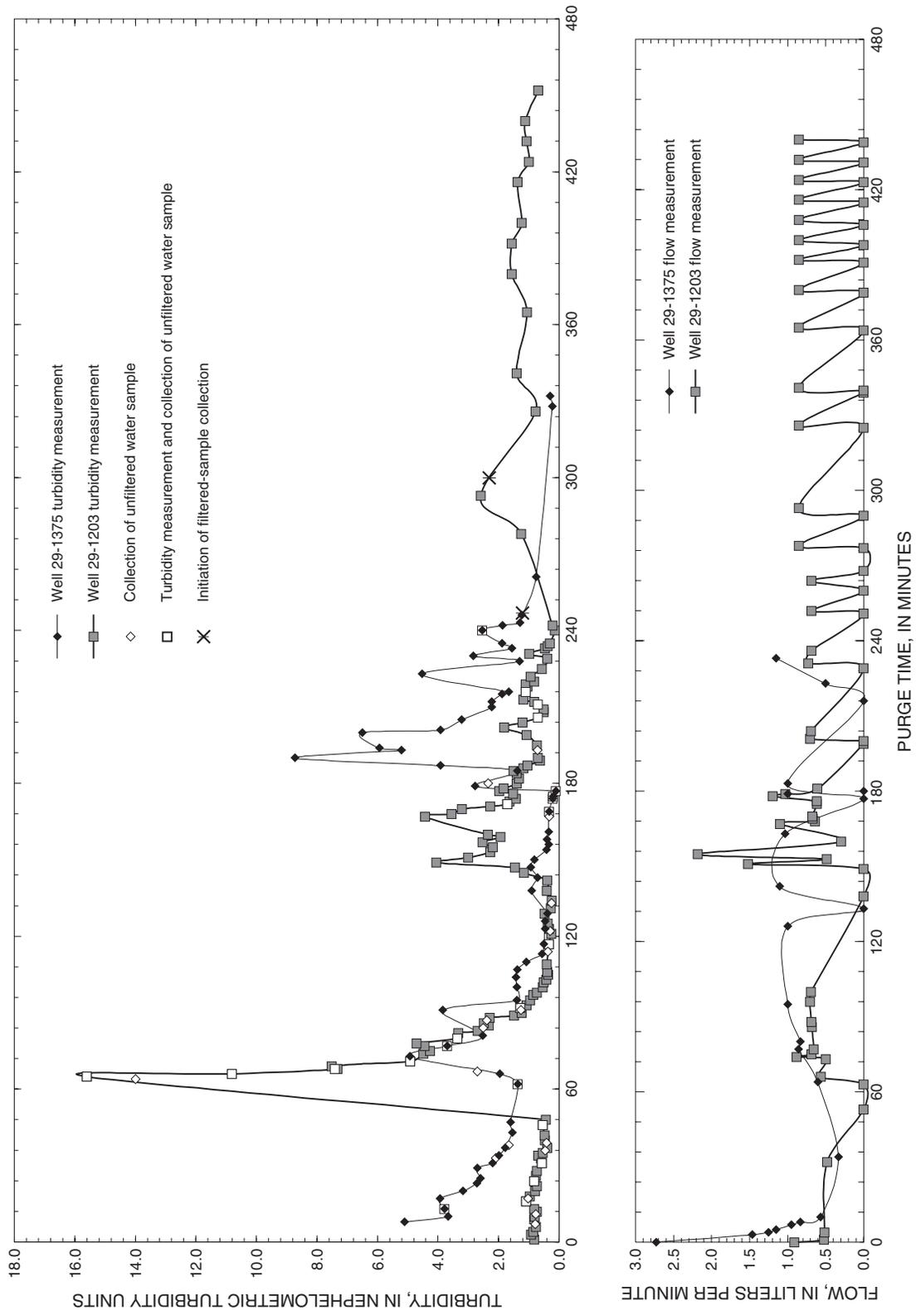


Figure 8. Turbidity and purging rate for the observation wells at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999-2000.—Continued

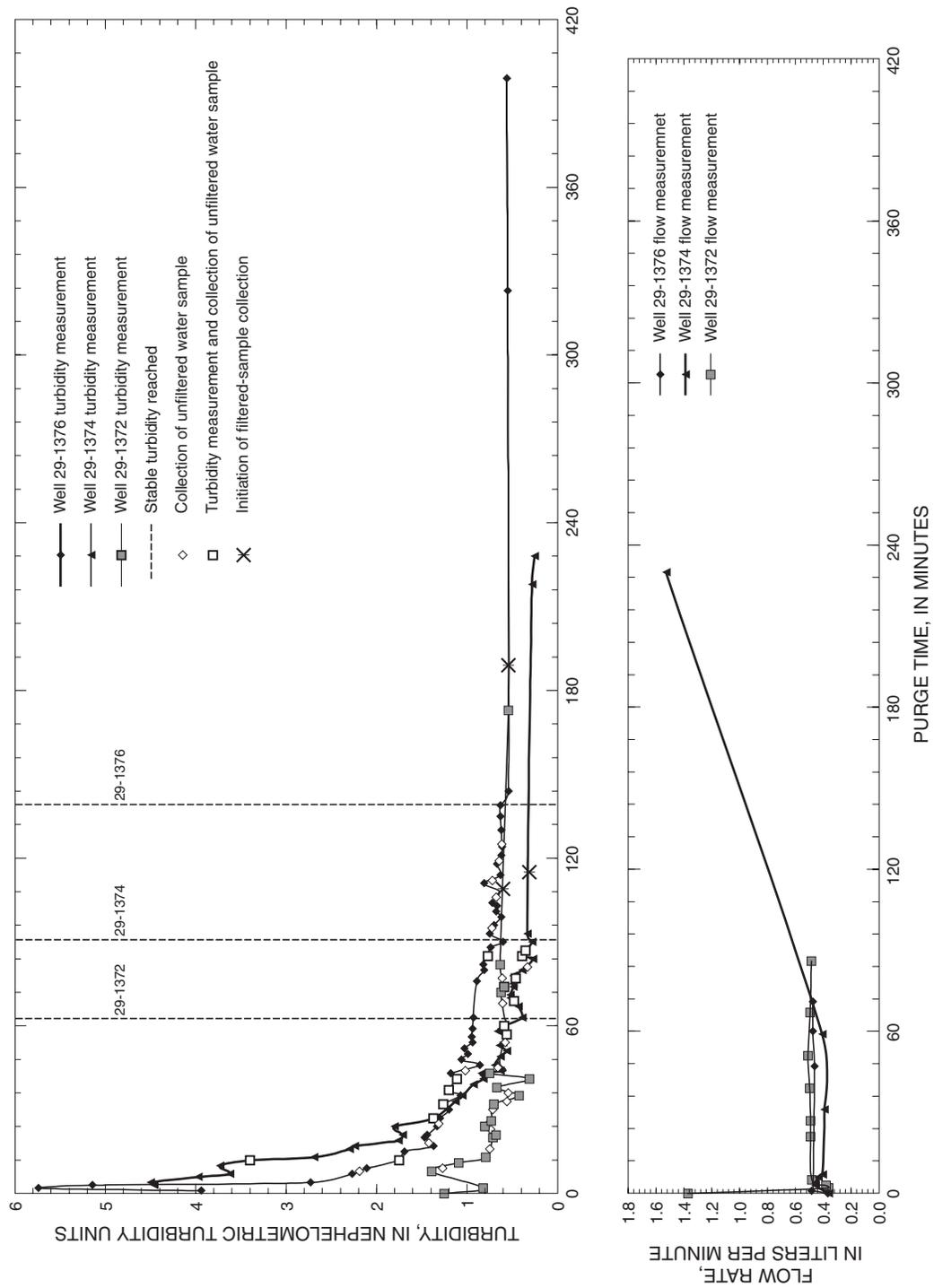
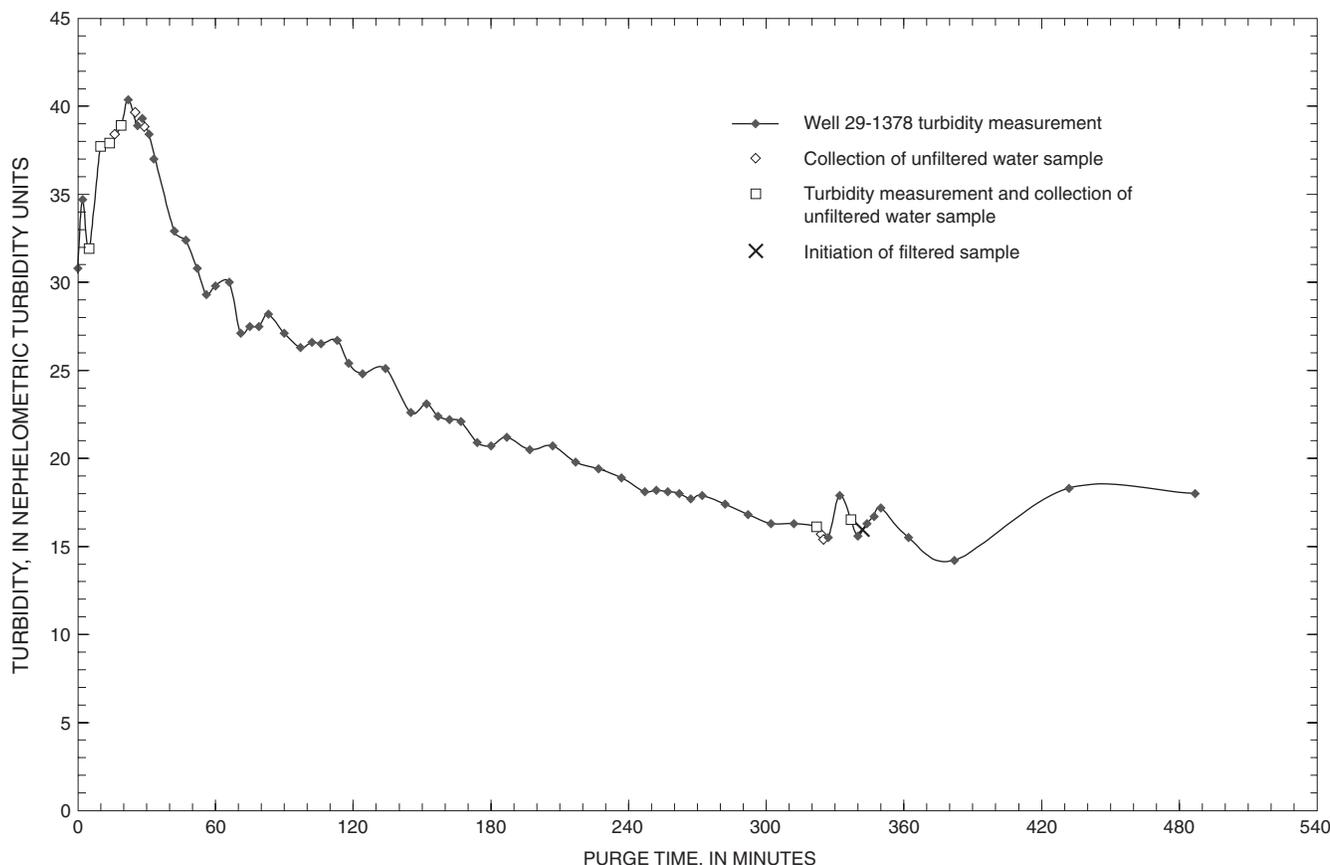


Figure 8. Turbidity and purging rate for the observation wells at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000. —Continued



**Figure 8.** Turbidity and purging rate for the observation wells at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

presented here are similar to those of Ryan and Gschwend (1990), who report that 10 to 20 casing volumes of water may need to be purged during 6 hours or more before stable turbidity is reached. The resuspension of settled particles with the initiation of sampling, characterized for this investigation by detailed monitoring of turbidity throughout well-purging activities (fig. 8), is consistent with the result of Backhus and others (1993), Kearn and others (1992), and Gibs and others (2000) and may give the false impression that the water in the aquifer system is turbid.

Even with low-flow sample-collection techniques, considerable purging is required to reduce turbidity. Unfiltered samples collected by means of the traditional approach of initiating sampling after purging a fixed volume or time interval could contain particulates mobilized by the surging action of pumping, and a positive bias in trace-element concentration could result. This result is especially likely when the samples are collected from infrequently purged observation wells, such as those utilized in this study. The field experiments conducted by Gibs and others (2000) and Szabo and others (2002) demonstrate the potentially large effect of turbidity on concentrations; particle-rich turbid samples collected soon after purging was initiated contained greater trace-element concentrations than samples with low turbidity collected after substantial purging.

Strict documentation of turbidity in the sampling program presented here provides an indication that stable turbidity was reached within the limits of available field-detection instruments. Precautions were taken to reduce particulate artifacts in samples analyzed for trace elements and radionuclides. Concentrations of Pu, Am, U, and Th in water can be expected to be reasonably representative of that in the aquifer system within the limits of the analytical capability.

### Concentrations of Plutonium, Americium, Uranium, and Thorium in Water

The concentrations reported for Pu isotopes and Am-241 are, in all but one case, less than the 0.1-pCi/L LRL for these radionuclides and are, in all but a few isolated cases, less than the SSMDC of the counting instrument (table 7). Concentrations greater than the SSMDC are the true detection of radiation at greater than the 95-percent degree of confidence. There is less than a 5-percent chance of a false negative, the situation where radiation is present but is “falsely” not recorded on the instrumentation; see Currie (1968) and Strom and MacLellan (2001). Many measured concentrations were less than 0.01 pCi/L and were substantially less than the LRL and

the SSMDC. Many of the concentration results from the study are negative numbers; the negative numbers indicate the results of analysis were actually less than the amount typical of routinely measured background radiation. In other words, negative radionuclide concentration results indicate that the radioactivity of the sample could not be distinguished from, and, in fact, was lower than typical background radioactivity in the laboratory.

The raw analytical concentration results for each radionuclide ideally are interpreted in the context of the plus or minus error associated with the 2-Sigma P.E. In the few cases where the reported analytical concentration is slightly greater than the SSMDC, the reported analytical concentration result minus the 2-Sigma P.E. is less than or equal to the SSMDC. This result indicates that, although a minute amount of radiation above background levels was detected, at a 95-percent confidence level the analytical result cannot be differentiated quantitatively from the SSMDC.

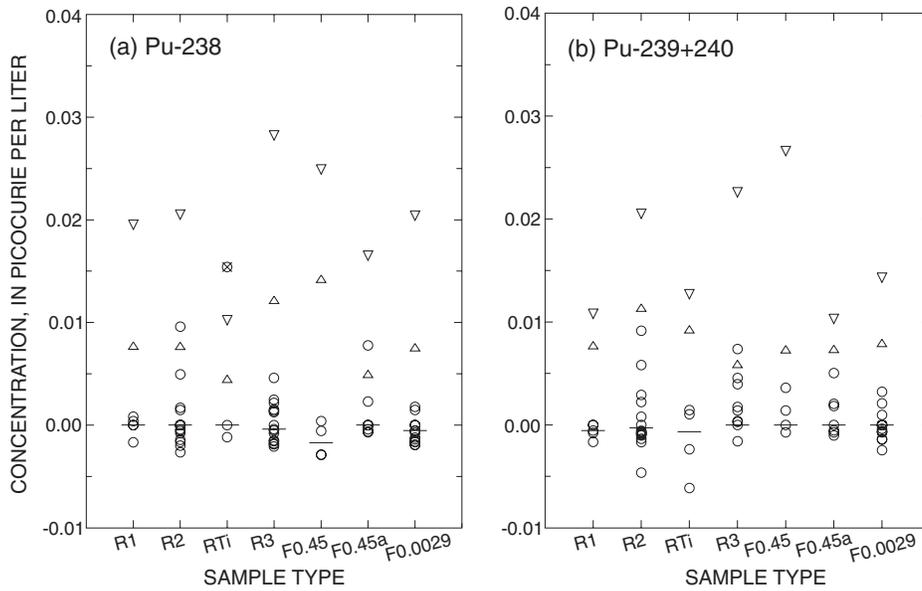
Concentrations of each of the radionuclides are shown for all wells for each sample type (unfiltered, filtered, tangential-flow ultra filtered) in figure 9. Where sequential duplicates were collected, the concentrations of these samples are included. For each sample type, the median of the individual concentrations of each radionuclide for all wells was computed and is indicated in figure 9. For each sample type, the median of the individual SSMDCs for each radionuclide was computed and is indicated in figure 9; the maximum SSMDC for each radionuclide for each sample type also is provided. Individual sample concentrations also were compared to the median and maximum SSMDC (fig. 9), thereby placing constituent concentrations in context not only with the individual SSMDC, but with the typical SSMDC (median) and the most conservative SSMDC with regard to analytical capability (maximum SSMDC). Most constituent concentrations were less than the individual as well as the median SSMDC; that is, the radiation could not be considered greater than background at that instant in time. The LRL of 0.1 pCi/L is not shown in figure 9 because all but one constituent concentration was substantially less than this value. A concentration reported at or greater than the LRL was of concern because, at this level, the result was considered to be readily verifiable (reproducible) and quantifiable using routine procedures. Concentrations of radionuclides that exceeded the individual SSMDCs but were substantially less than the LRL were considered with caution because the amount of radioactivity present was so small that it could not be considered to be quantifiable above background radiation on a routine basis. Furthermore, at the concentration level of the SSMDC, a small but nevertheless real likelihood remains of the occurrence of "false positive" results when instruments indicate the presence of radioactivity though none is truly there. In the few cases where the reported concentration was slightly greater than the SSMDC, the result was carefully evaluated to determine the significance in the context of the 2-sigma P.E., the SSMDC, the LRL, and the information gained from quality-assurance samples, including replicates and equipment blanks; each of these samples is discussed below. The results were termed "quali-

fied" if concentration results were not verified by analysis of sequential replicate or laboratory duplicate samples or were not consistent with results of concurrent samples. Concentrations of the radionuclides that exceed the individual sample SSMDCs are denoted with a different symbol in figure 9 than those that were less than the SSMDCs.

Concentrations of radionuclides in the colloid-bearing fraction in the retentate flow that does not pass the tangential-flow ultrafilter could require correction based on the concentration factor (CF) used during tangential-flow ultrafiltration (See concentration factor (CF) in Glossary; Hoffman and others, 1981; 2000). The CF was determined in the field (Szabo and others, 2002), but the use of the CF was not necessary for computing the radionuclide concentrations determined for the samples because results are less than the SSMDC.

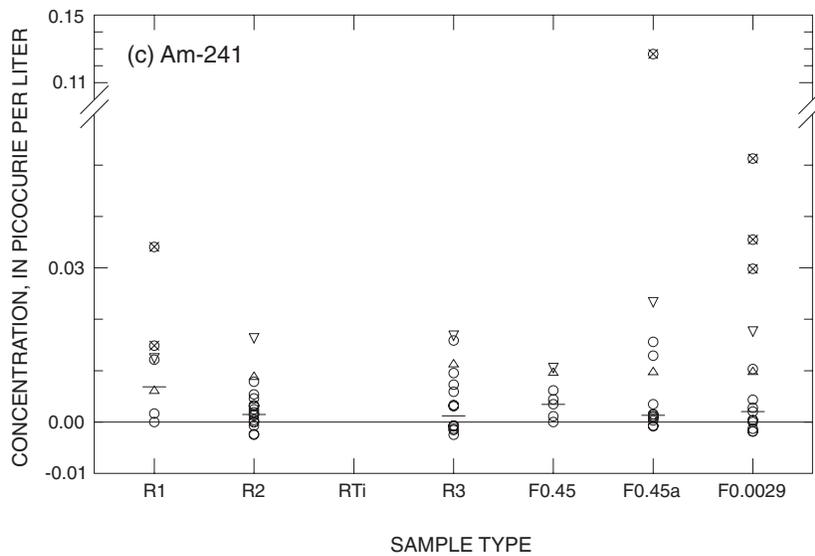
The median concentration of isotopes of Pu-238 and Pu-239+240 are about zero in all water-sample types (figs. 9a, 9b) and are much less than either the median or maximum SSMDC. Many negative concentrations were reported. In the few cases where the reported analytical result is slightly greater than the individual SSMDC, the reported analytical result minus the 2-Sigma P.E. is less than the SSMDC, indicating that quantification above the SSMDC is uncertain.

The maximum concentration of Pu-238, shown in figure 9a as a "qualified" result, was 0.0154 pCi/L and was present in an unfiltered sample from well 29-1203 that was collected during well purging when the water had moderate turbidity (2.29 NTU). The reported analytical result minus the 2-Sigma P.E. of 0.01 pCi/L is slightly greater than the individual SSMDC but is nearly an order of magnitude less than the LRL. The well is outside the fence adjacent to the drainage ditch where runoff from fire fighting was diverted. None of the other filtered or unfiltered water samples from this well (29-1203) contained a Pu-238 concentration that exceeded individual SSMDCs. Furthermore, the sample did not contain detectable Pu-239+240. On the basis of this information, this single result was "qualified" because a concentration of the same order of magnitude was not reproduced in any other sample from the well. At about the level of the SSMDC, the likelihood of false positive results is about 5 percent; thus, for 90 samples at this concentration level, one or more false positive results would not be unexpected. Because the collected sample was moderately turbid relative to the final measured turbidity of 1.12 NTU and was unfiltered, the possibility of a "hot particle" could not be completely ruled out, although the absence of detected Pu-239+240 in the same sample seems to indicate that the most plausible explanation is the presence of minor laboratory "noise". Liator (1999) reports that "...errors (that) were originated from the high variability in plutonium activity..." in soils (that can be attributed in part to "hot particles") pose substantial difficulty for any sampling program assessing dispersion of these manmade radionuclides. In an earlier study, Sill (1975) reached the same conclusion regarding environmental sampling of dispersed plutonium, stating "...the major problems arise in obtaining sufficient samples... and homogeneous samples for analysis."

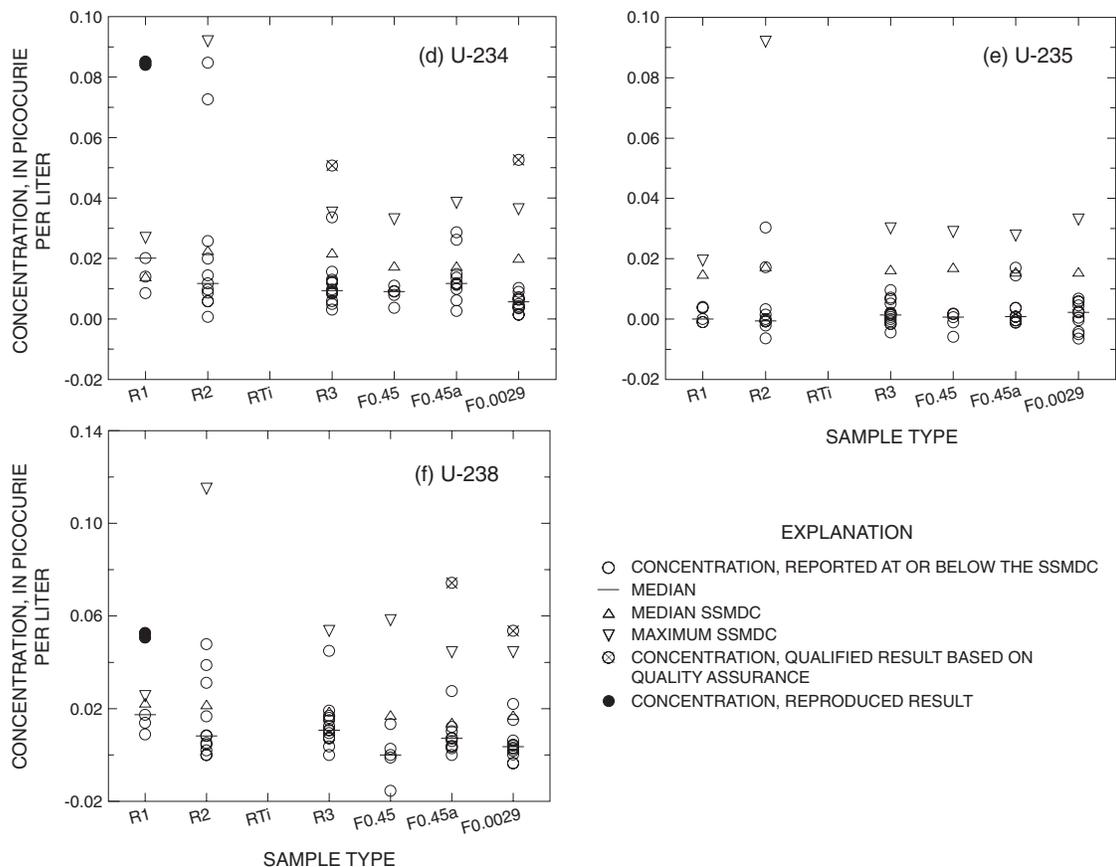


EXPLANATION

- CONCENTRATION, REPORTED AT OR BELOW THE SSMDC
- MEDIAN
- △ MEDIAN SSMDC
- ▽ MAXIMUM SSMDC
- ⊗ CONCENTRATION, QUALIFIED RESULT BASED ON QUALITY ASSURANCE



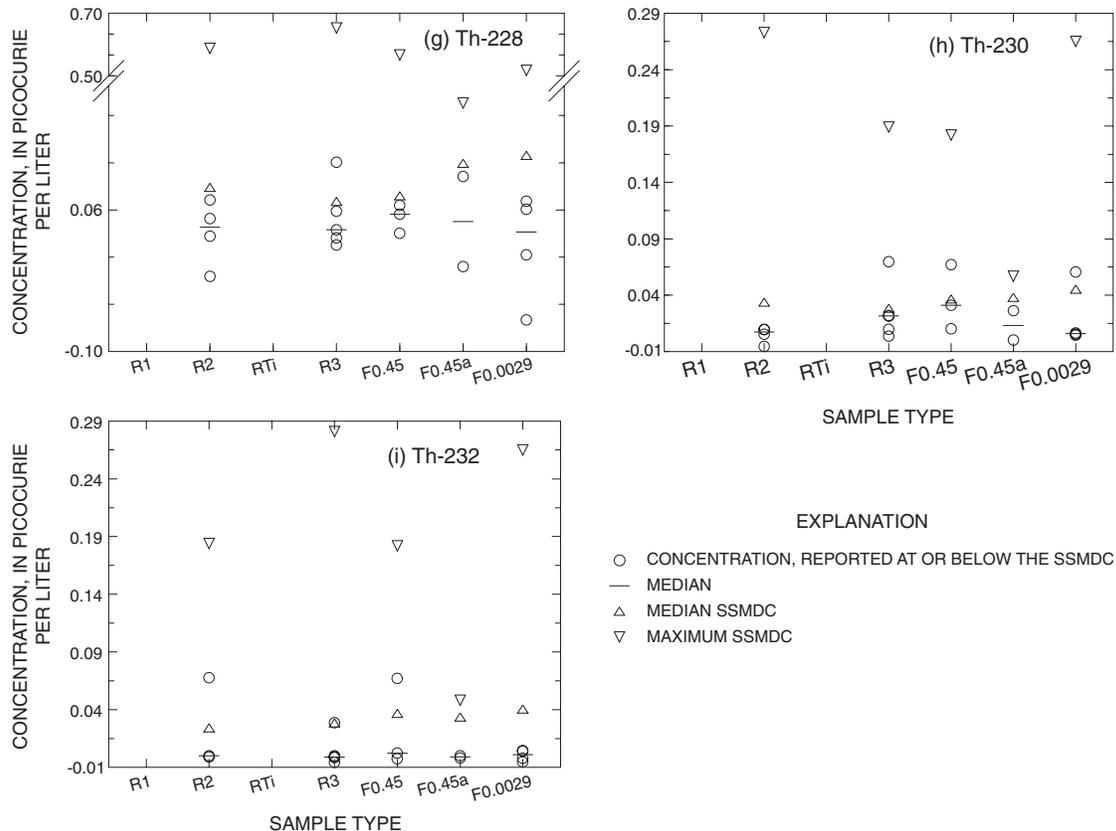
**Figure 9.** Concentrations of (a) plutonium-238 (Pu-238), (b) plutonium-239+240 (Pu-239+240), (c) americium-241 (Am-241), (d) uranium-234 (U-234), (e) uranium-235 (U-235), (f) uranium-238 (U-238), (g) thorium-228 (Th-228), (h) thorium-230 (Th-230), and (i) thorium-232 (Th-232) in water samples from observation wells at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000, grouped by sample collection technique.



**Figure 9.** Concentrations of (a) plutonium-238 (Pu-238), (b) plutonium-239+240 (Pu-239+240), (c) americium-241 (Am-241), (d) uranium-234 (U-234), (e) uranium-235 (U-235), (f) uranium-238 (U-238), (g) thorium-228 (Th-228), (h) thorium-230 (Th-230), and (i) thorium-232 (Th-232) in water samples from observation wells at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000, grouped by sample collection technique.—Continued

The median concentrations of the radioisotope Am-241 are about zero in all water-sample types but one (fig. 9c) and are generally much less than either the median or maximum SSMDC. Many negative values for Am-241 concentrations were reported for all sample types. The sole exception is the median concentration of Am-241 in the initial unfiltered samples from the wells that also tended to be the most turbid; for these initial unfiltered samples with substantial particle concentration, the median Am-241 concentration was about 0.01 pCi/L, a result that is about equal to the median SSMDC for that sample type. Two turbid, unfiltered water samples from well 29-1371 with 5.46 and 8.02 NTU contained Am-241 concentrations of 0.0149 and 0.0341 pCi/L, respectively, that were greater than the respective SSMDC; a third unfiltered sample contained an Am-241 concentration that exceeded the SSMDC, but the result did not exceed the SSMDC when the 2-sigma P.E. was considered (subtracted). For two of the turbid samples collected at about the same time, the Am-241 concentration minus the 2-Sigma P.E. was slightly less than the SSMDC (fig. 9c), indicating that the concentration cannot be reliably distinguished from the SSMDC. The Am-241 concentrations for the initial unfiltered samples are considered “qualified.”

The maximum concentration of Am-241, shown in figure 9c as a “qualified” result, was 0.127 pCi/L in a sample from well 29-1371 that was filtered through the 0.45- $\mu$ m capsule filter (F0.45a). The sample result minus the 2-Sigma P.E. of 0.0337 pCi/L was slightly less than the LRL of 0.1 pCi/L. The concentration of Am-241 in a sequential duplicate sample (table 7B) that passed the same filter was less than the individual SSMDC of 0.0145 pCi/L, however. The concentration of Am-241 in the retentate sample (F0.45) that passed over the 0.0029- $\mu$ m ultrafilter and also passed through the 0.45- $\mu$ m capsule filter was 0.0129 pCi/L, but the analytical result minus the 2-Sigma P.E. of 0.0088 pCi/L equaled the SSMDC within the rounding error (third significant figure). The corresponding permeate samples were filtered through the 0.0029- $\mu$ m ultrafilter (F0.0029), collected, and analyzed in triplicate; the Am-241 concentration was less than the SSMDC in one of the replicates (tables 7A and 7B). Am-241 concentrations were 0.0298 and 0.0513 in the other replicates, and the reported analytical results minus the 2-Sigma P.E. were greater, albeit barely, than the SSMDC (fig. 9c). The corresponding unfiltered samples (R3), collected while filtration progressed, did not contain concentrations of Am-241 greater than the SSMDC, however (fig. 9c).



**Figure 9.** Concentrations of (a) plutonium-238 (Pu-238), (b) plutonium-239+240 (Pu-239+240), (c) americium-241 (Am-241), (d) uranium-234 (U-234), (e) uranium-235 (U-235), (f) uranium-238 (U-238), (g) thorium-228 (Th-228), (h) thorium-230 (Th-230), and (i) thorium-232 (Th-232) in water samples from observation wells at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000, grouped by sample collection technique.—Continued

Concentrations of Am-241 indicate a lack of correspondence among the filtered and unfiltered water samples from well 29-1371 and among replicates of the filtered samples. On the basis of this information, the Am-241 concentration results from the filtered samples were qualified because detectable Am-241 concentrations of the same order of magnitude were not routinely reproduced in the unfiltered samples collected at about the same time from the well. The most likely explanation for the lack of reproducibility of Am-241 concentrations in the filtered samples is minor laboratory “noise.”

The possibility of Am-241-bearing “hot particles” occurring randomly in turbid unfiltered samples cannot be ruled out. The possibility that a colloidal “hot particle” containing Am-241 passed through the 0.45- $\mu\text{m}$  capsule filter, thus, also cannot be completely ruled out as contributing to the presence of Am-241 in the filtered sample. A similar explanation, a rarely occurring “hot particle”, is possible for sample (R1) with the most turbidity, collected from this well (29-1371) just after purging was initiated. The filtered samples were collected at the end of purging when the purged water was not turbid (final turbidity less than or about 1 NTU; tables 3 and 7). Szabo and others (2002) show, however, that a minute amount of particles not

quantifiable even with the most highly sensitive analytical technique (laser light-scattering) were present in ground water with turbidity less than 1 NTU. The occasional but not reproducible presence, of Am-241 in the samples from well 29-1371 typically at concentrations less than 0.1 pCi/L indicates that if “hot particles” are truly present, they are few in number (possibly as few as 1–5 “hot” particles per liter) and not readily quantifiable by the sampling technique used.

The concentration of Am-241 in the permeate flow from the 0.0029- $\mu\text{m}$  ultrafilter (F0.0029) minus the 2-Sigma P.E. was slightly greater than the SSMDC for the sample from well 29-1379. The duplicate sample of permeate flow from the 0.0029- $\mu\text{m}$  ultrafilter was spilled in the laboratory before it could be analyzed, so confirmation of the Am-241 concentration was not obtained. The corresponding unfiltered samples (R3) did not contain detectable Am-241, however (fig. 9c). Well 29-1379 is located in an area that probably does not intercept water from flow paths that could have originated near Shelter 204 (fig. 2). Therefore, Am-241 concentration for the permeate-flow sample from well 29-1379 is considered “qualified” and probably represents laboratory “noise” (fig. 9c).

The medians of concentrations of the isotopes of U-238 and U-234 are about 0.01 pCi/L in all types of the water samples, except one (figs. 9d and f), and typically are less than either the median or maximum SSMDC. Occasionally, negative concentrations were reported for U isotopes, indicating that some samples contained no U. The exception is the group of initial unfiltered (R1) samples; the median U-238 and U-234 concentrations in this sample type were about 0.02 pCi/L, a result that is about equal to the median SSMDC for that sample type. These initial unfiltered samples also tended to be the most turbid. The particles in the sample may contain U isotopes; the sediment that composes the aquifer system contains small quantities of U (Szabo and others, 1997). The low concentration of U isotopes in the ground-water samples at the Facility is typical for water from the Kirkwood-Cohansey aquifer system as a whole; Kozinski and others (1995) report a median concentration of 0.03  $\mu\text{g/L}$  for 80 samples of water from the aquifer system. Kozinski and others (1995) also measured U-234 to U-238 isotope ratios of about 1:1 in water from the Kirkwood-Cohansey aquifer system. Assuming the isotope ratio of naturally occurring U in water from the aquifer system is 1:1, the median concentration of U (0.03  $\mu\text{g/L}$ ) determined by Kozinski and others (1995) would be the equivalent of 0.02 pCi/L of radioactivity resulting from naturally occurring U isotopes (0.67 pCi/ $\mu\text{g}$ ; see Schlein, 1992), which is nearly identical to the median U isotope concentration in water from the aquifer system at the Facility.

The initial unfiltered sample from well 29-1378 and a sequential replicate contained U-238 and U-234 concentrations of 0.05 and 0.08 pCi/L, respectively, and turbidity was 38 and 38.9 NTU, respectively (tables 7A, 7B). The similar results in replicate samples indicate that the U concentration is reproducible even in turbid water. This reproducible result indicates that naturally occurring U is present in small amounts, especially in particulates present in the turbid unfiltered samples. It is also likely, however, that the particulates in this turbid initial purge water were not actually mobile in the aquifer system but were part of the particulate material that settled to the bottom of the well and resuspended during the sampling event. (Well 29-1378 was not redeveloped before sampling and remained turbid throughout purging.) It is likely that turbid samples (turbidity >100 NTU) from improperly developed and purged wells contain large amounts of resuspended sediment and minor amounts of associated uranium. The association between trace elements and sediment resuspended during purging has been documented by Gibs and others (2000).

Concentrations of the isotopes of Th typically are less than either the median or the maximum SSMDC (figs. 9g–i). Occasionally, negative concentration results were reported. The concentration of Th isotopes in ground water typically is low because Th is insoluble in virtually all natural conditions (Langmuir and Herman, 1980). The presence of minor amounts of Th in sediments of the aquifer system has been documented by Szabo and others (1997); thus, as for U, the presence of minor amounts of Th in turbid samples may not be unreasonable.

Gross alpha-particle activity and gross beta-particle activity are low. Gross alpha-particle activity typically was less than the LRL of 3 pCi/L, and gross beta-particle activity in most samples was below the LRL of 4 pCi/L. These crude measurement techniques can be good indicators of the presence of radionuclides whose concentrations are not specifically determined but that are greater than the LRL (by 2–3 pCi/L). The “gross” analytical techniques cannot detect minor amounts of radiation, however. The measurement 2-Sigma P.E. is typically about the same magnitude as the LRL for samples with activities of about the LRL because of the substantial analytical uncertainty of the “gross” techniques. If gross alpha-particle or beta-particle activity of considerable magnitude were detected, the additional radiochemical analyses conducted to determine the concentrations of specific nuclides also could be used to determine the exact nature of the radiation-emitting nuclides. On the other hand, in the absence of gross radioactivity of a magnitude greater than the LRL, as is the case at the Facility, these “gross” measurement techniques will not provide useful screening information regarding radioactive contamination.

Water in the Kirkwood-Cohansey aquifer system, especially in the southwestern part of the system (southwestern New Jersey), typically contains gross alpha-particle activity of about 10 to 15 pCi/L, but does not always contain naturally elevated gross alpha-particle activity, especially in the Pine Barrens Preserve area. The low activities of gross-alpha and gross-beta particles in water at the Facility are in the range reported previously for the Pine Barrens Preserve in northern Atlantic County, south-central Burlington County, and central Ocean County (Szabo and others, 1997, table 2B).

The only notable trend in radioactivity at the Facility was that gross alpha-particle activity was highest in the water from the shallowest two wells; pH was lowest in the shallow waters. (Data are sorted by well depth in the tables with the intent of evaluating the approximate depth of penetration of any man-made radionuclide contamination. See Rice and Szabo (1997) for discussion of depth of penetration of manmade contaminants into the Kirkwood-Cohansey aquifer system). The results from this sampling experiment at the Facility are consistent with those reported for the Kirkwood-Cohansey aquifer system by Szabo and others (1997), who show that the highest concentrations of the naturally occurring radionuclides (radium-226 and radium-228) in water from the aquifer system are found at shallow depths where pH is lowest. The low but detectable gross alpha-particle activity at shallow depths in relation to non-detectable radioactivity at substantial depth is consistent with the typical conditions of the aquifer system.

On the basis of the results of analyses reported in table 7 and shown in figure 9 and a review of the qualified data, no evidence was observed of any unqualified and routinely reproducible, detectable, and quantifiable manmade radionuclide contamination in any of the set of raw unfiltered or filtered water samples from the 10 observation wells. All quality-assurance data, including results of laboratory duplicates and sequential field replicates, are in agreement with the results of the analyses of initial environmental samples that indicate no discernible

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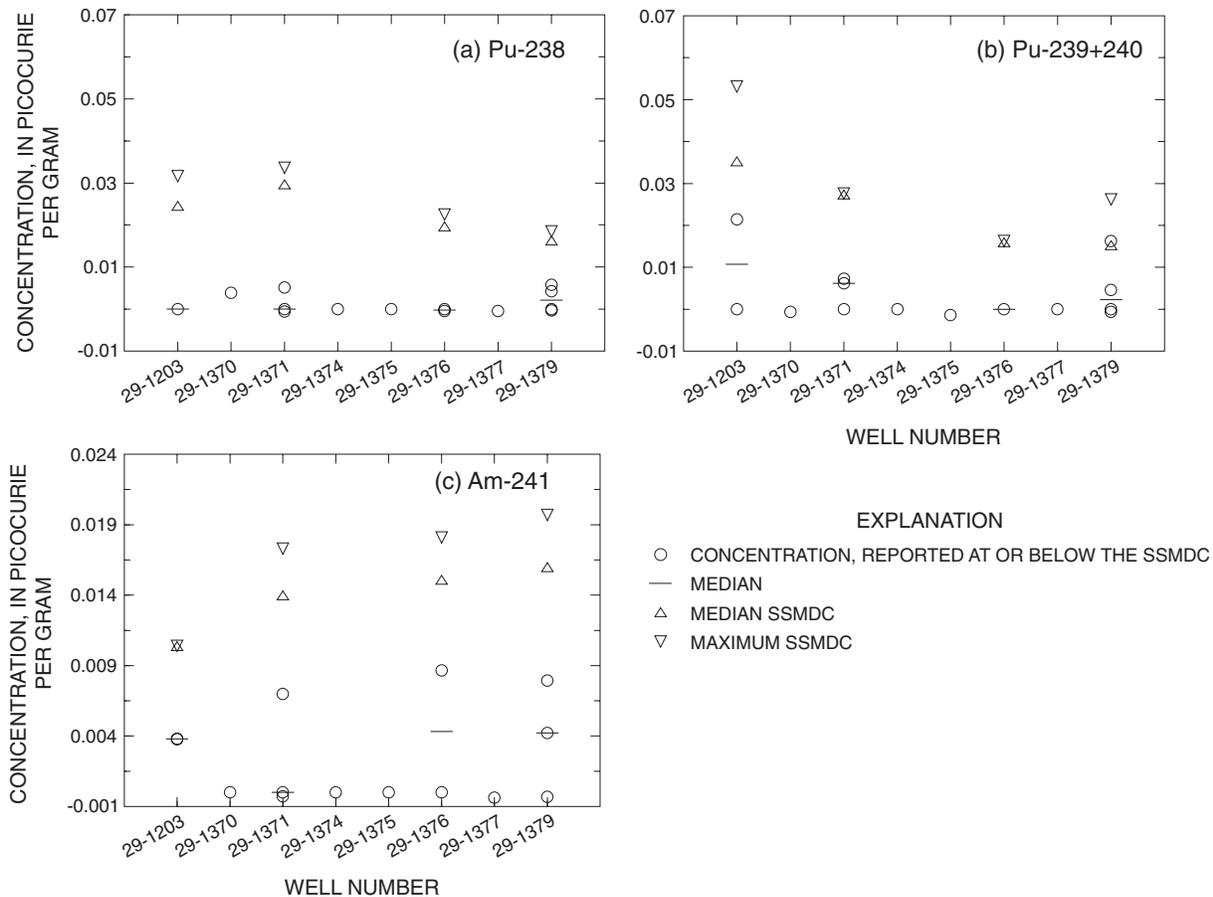
radionuclide concentrations are present at greater than background levels (tables 6, 7A, and 7B). Results of analyses of equipment blanks indicate that random contamination from sample handling was not introduced. Thus, there is no evidence of manmade radionuclide contamination in the aquifer system in the form of particulates, colloids, or truly dissolved radionuclides.

**Concentrations of Plutonium, Americium, and Uranium in Settled Sediment**

The concentrations of isotopes of Pu and Am-241 in settled sediments recovered from the bottom of the observation wells were less than the SSMDC (fig. 10; table 8). The concentrations are well below the 0.1 pCi/g (picocuries per gram) considered the average background fallout concentration level reported by Earth Technology Corporation (1991) and are sim-

ilar to those low levels noted by Lee and others (1998) for fall-out in soil in New Mexico and by Hulse and others (1999) for background levels in soil in Colorado.

The concentrations of U isotopes in these well-bottom sediments generally were less than the SSMDCs, which were substantially less than 0.1 pCi/g. The concentrations of U-238 and U-234 were greater than the SSMDCs and ranged from about 0.05 to 0.25 pCi/g in sediment samples retrieved from the bottom of three observation wells, 29-1371, 29-1376, and 29-1379 (fig. 10; table 8). U-isotope concentrations were within the range of naturally occurring U-isotope concentrations in the aquifer sediments. Concentrations of Ra-226 in samples of sand from the Kirkwood-Cohansey aquifer system from southwestern New Jersey were at about the same activity level, typically 0.05 to 0.2 pCi/g (Szabo and others, 1997); this decay product of U was present in solids at activities of about the same level as U-238. The isotopic ratio of U-234 to U-238 in the sediment samples of about 1:1 also is consistent with that of

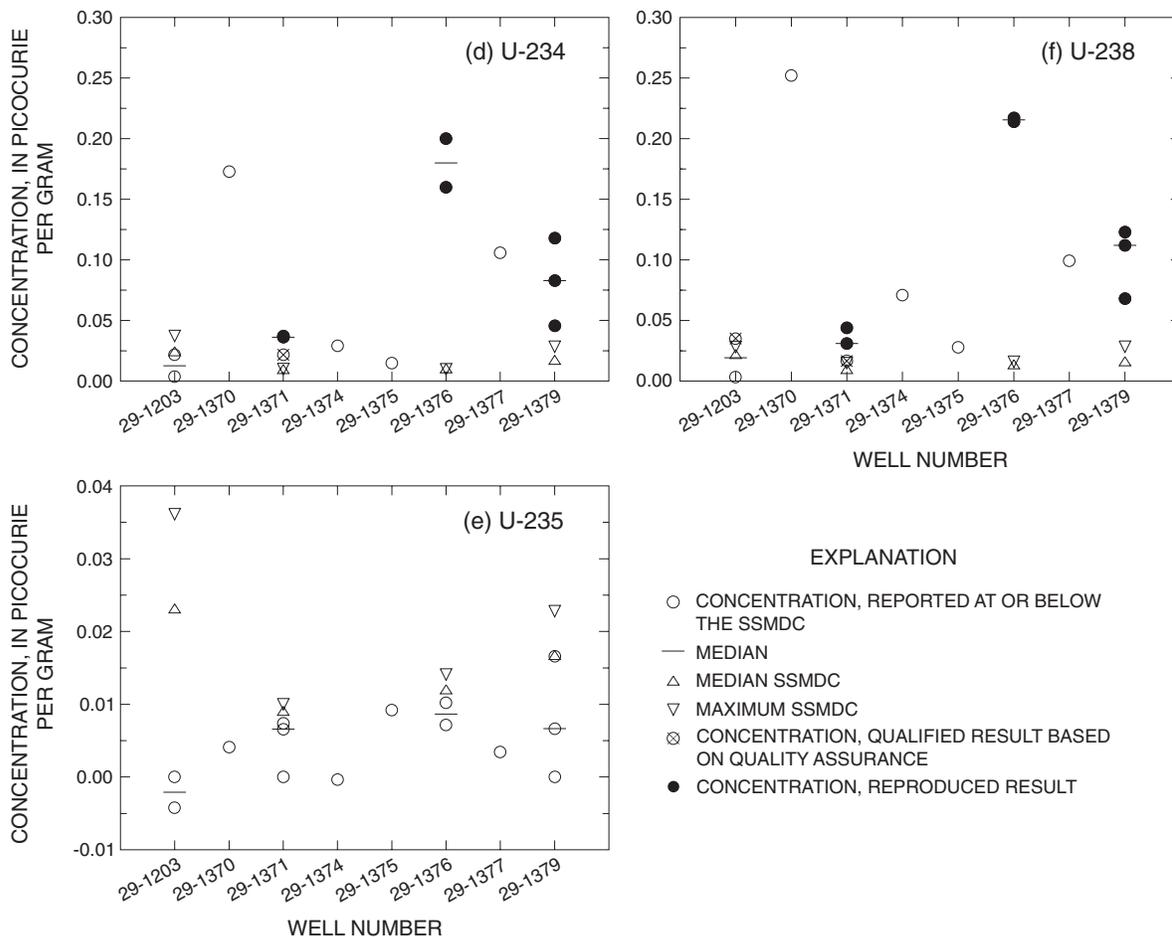


**Figure 10.** Concentrations of (a) plutonium-238 (Pu-238), (b) plutonium-239+240 (Pu-239+240), (c) americium-241 (Am-241), (d) uranium-234 (U-234), (e) uranium-235 (U-235), and (f) uranium-238 (U-238) in samples of sediment settled to the bottom of observation wells at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999.

natural sediment (Osmond and Cowart, 1976). (Unfortunately, the bottom-sediment sample from well 29-1372 was accidentally discarded at the laboratory before U analysis was complete, and a sediment sample was not recovered from the bottom of well 29-1378.)

The low Pu, Am, and U concentrations indicate that there is not at present (2000) a reservoir of sediment contaminated with manmade radionuclides in the bottom of the observation wells. The result is consistent with the absence of quantifiable concentrations of manmade radionuclides in samples of even the most turbid water collected initially from the observation wells. (The U-234 and U-238 present in a few turbid samples with an isotopic ratio indicative of natural, not industrial, origin are likely derived from aquifer system sediment settled to the bottom of the wells.) Of the wells with detectable U in bottom sediment, only well 29-1379 contained detectable U (U-234) in an initially turbid water sample. (Replicate and duplicate samples selected for analysis at random were not chosen for analysis for the concentration of U for well 29-1379; therefore, the sample result, although reasonable, could not be verified with a replicated sample.)

Water samples collected with strict adherence to low-flow protocols have low turbidity and particulate concentrations, and are representative of the shallow ground water at the Facility, as opposed to the samples collected without such protocols. Before this study, water samples from the aquifer system at the Facility were collected without the use of low-flow sample-collection techniques and purging to stabilize and minimize turbidity; therefore, the samples could have contained a much higher concentration of particulates, as well as concentrations of U associated with those particulates, than samples collected for all sampling events during this study with the strict adherence to low-flow sampling protocols. Szabo and others (2002) demonstrated with water samples from the Facility that, even when low-flow sampling techniques are used, initial samples collected from observation wells before turbidity is stabilized could contain considerable concentrations of particulates and trace elements associated with these particulates. Despite that Pu and Am were not detected in the well-bottom sediments, the presence of naturally occurring U and Th could have resulted in spectral interference in turbid sediment-laden water samples collected in the past by use of the bailing technique.



**Figure 10.** Concentrations of (a) plutonium-238 (Pu-238), (b) plutonium-239+240 (Pu-239+240), (c) americium-241 (Am-241), (d) uranium-234 (U-234), (e) uranium-235 (U-235), and (f) uranium-238 (U-238) in samples of sediment settled to the bottom of observation wells at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999.—Continued

## Summary and Conclusions

The U.S. Geological Survey (USGS), in cooperation with the U.S. Air Force (USAF), designed a detailed radiochemical sampling field experiment at the BOMARC Missile Facility in the Pine Barrens Preserve in Ocean County, New Jersey, to address concerns regarding potential radionuclide contamination in the unconfined aquifer (Kirkwood-Cohansey aquifer system) and the quality of analytical results based on sampling technique. A fire in 1960 at the Facility and the subsequent release of plutonium (Pu) from a warhead to the environment have raised environmental and regulatory concerns regarding the potential for Pu dispersal and ground-water contamination. Of special concern was the possible migration of colloid-size particles in the aquifer system because these are known to facilitate transport of Pu and the Americium (Am) products of Pu decay. A review of radiochemical data previously obtained during numerous samplings at the site during 1985–94 indicated, however, that previous sampling techniques (bailing) and variations in particulate matter in the samples, as well as the lack of documentation of this variability, did not lead to reproducibility of analytical results. In order to address the environmental and regulatory concerns, specific attention was placed on developing a stringent sampling protocol to ensure the collection of samples that are representative of water in the Kirkwood-Cohansey aquifer system and various size particles to determine if any contaminants were sorbed to potentially mobile particles in the ground water, especially colloids of 0.45 micrometer ( $\mu\text{m}$ ) or less. The sampling protocol was designed to determine the occurrence of any particulate, colloidal, and dissolved-phase concentrations of radionuclides present in the unconfined aquifer system that might be attributable to release during the fire. Isotopes of plutonium (Pu-238 and Pu-239+Pu-240), Am (Am-241), and uranium (U) (U-238 and U-234) that could be associated with the warhead were selected as the constituents to be analyzed. The concentrations of the isotopes of thorium (Th) also were determined in water samples from some of the wells. Gross alpha-particle and beta-particle activity were measured to provide overall screening for radionuclides in the ground water and for comparison with previous sampling results for the Facility and previously obtained data on background concentrations of radionuclides in samples from the aquifer system.

Water samples were collected from 10 observation wells and bottom-sediment samples were collected from 9 of the wells for radiochemical analysis from August 1999 to February 2000. All observation wells sampled have screened intervals in the unconfined aquifer system underlying the Facility. Sampling was performed by collecting sequential samples of raw unfiltered and filtered water using low-flow purging techniques coupled with size fractionation with the use of tangential-flow ultrafiltration. Turbidity was monitored continuously to characterize changes in particulate matter during purging and sampling. Turbidity was used to determine the most appropriate times for sample collection. Initial turbid purge water was sampled unfiltered, and additional unfiltered

samples were collected as purging progressed and turbidity decreased. Where possible, the final unfiltered and filtered samples were not collected until stable ( $\pm 0.8$  nephelometric turbidity units (NTU), four consecutive readings, each 5 minutes apart) turbidity of less than 5 NTU was achieved. Stable turbidity was achieved at all but two of the wells. Filtered water was collected through various nominal pore-size filters using standard filtration and tangential-flow ultrafiltration techniques after turbidity stabilized.

A certified laboratory performed the radiochemical analysis. Standard alpha spectroscopic techniques were used to determine concentrations of alpha-particle emitting radionuclides of Pu, Am, U, and Th in water, and after digestion in sediment. Raw (unrounded and uncensored) concentration results are reported to allow for comprehensive data evaluation. Extensive quality assurance, including analysis of blank and replicate samples, verified acceptable performance of the laboratory.

No evidence was observed of any detectable manmade radionuclide contamination in any of the well-bottom sediment samples, or in raw unfiltered or filtered water samples from any of the wells. All radionuclide concentrations from water samples, whether raw or filtered, were less than the 0.1 pCi/L (picocuries per liter) typically associated with routine laboratory (minimum) reporting levels (LRL) for these manmade radionuclides. The Am-241 concentration in one sample was about 0.1 pCi/L (the LRL of 0.1 pCi/L was within the bounds of the 2-Sigma P.E. for the sample result), but this result could not be reproduced in subsequent analyses of concurrent samples or splits. Most manmade radionuclide concentrations were less than 0.01 pCi/L, and negative values were commonly reported. These results indicated that the radioactivity of most of the samples could not be distinguished from background radioactivity in the laboratory. All quality-assurance data from laboratory duplicates and sequential field replicates are in agreement with the results of initial sample analyses that indicate no discernible concentrations above current background radiation were present. The analytical results for isotopes of Am-241 and Pu in sediments settled to the bottom of the wells also were below the LRL. The range of concentrations of U isotopes in the water and sediment matched nearly exactly those determined during previous regional studies of the water from the aquifer system and the aquifer sediment (about 0.2 pCi/g in sediment). Maximum concentrations of uranium isotopes (U-238 and U-234 were 0.05 and 0.08 pCi/L in water, respectively, and 0.25 and 0.20 pCi/g in sediment, respectively). Thus, the concentration of U does not indicate the presence of weapons-grade U-234 isotopes or atypically elevated U (above background levels) in either water or sediment. Gross alpha-particle activity and gross beta-particle activity were low ( $< 5.5$  pCi/L in all cases); these results are at the low end of the typical range reported previously for samples from the Kirkwood-Cohansey aquifer system in the Pine Barrens Preserve in southeastern New Jersey. No evidence was observed of manmade radionuclide contamination in the aquifer system as particulates or colloids or in the dissolved phase.

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# Glossary

## A

**Actinide** A group of chemical elements with an atomic number greater than 88, all of which are radioactive and have similar chemical properties (multiple valence states range from +1 to +7).

**Activity** The amount of radioactivity in a given volume of such material as water or air. For water, activity is generally expressed in units of picocuries per liter.

**Alpha radiation** Alpha radiation is composed of a particle, consisting of two protons and two neutrons, spontaneously emitted from the nucleus of a subset of radioactive elements (mostly the heaviest elements) during radioactive decay. Alpha radiation is ionizing radiation, meaning that it strips electrons from adjacent atoms as it passes. Alpha radiation cannot penetrate skin; thus, an alpha-particle emitting radionuclide must be ingested in order to contact internal tissue. Because of the large size, alpha particles are likely to collide with cell tissue, causing tissue damage. An accumulation of tissue damage in the cell nucleus may lead to cell mutation and potential cancer formation.

**Alpha radioactivity, gross** A laboratory measurement of total alpha radioactivity emitted by a sample. This measurement includes alpha particle radioactivity emitted by isotopes of naturally occurring uranium, thorium, radium, and progeny such as polonium, as well as alpha particles emitted from isotopes of plutonium or americium, which are not naturally occurring. Long-term measurement, usually conducted from 20 to 30 days after sample collection, measures only the amount of alpha radiation present from long-lived radionuclides, such as naturally occurring uranium-238 or radium-226 (half-life, 1,602 years), or the isotopes of plutonium and americium. The plutonium and americium isotopes considered in this study are alpha-particle emitting nuclides.

**Alpha radioactivity count** An analytical technique that specifies alpha radioactivity emitted by a chemically purified sample that contains only one radionuclide of interest. The alpha-

particle activity is counted in a low-background gas proportional counter.

**Alpha spectrometry** An analytical technique that specifies the amount of alpha radiation emitted at specified energy levels, thus, allowing determination of individual radionuclide concentrations (from known energy levels of alpha particles unique to each radionuclide). The gridded-pulse-ionization chamber is the most sensitive and most commonly used instrument.

**Americium** Americium is a radioactive actinide element derived from the radioactive decay of manmade plutonium.

## B

**Bailing (sampling technique)** A water sample is removed (abstracted) from a well by the process of lowering an empty container (usually a hollow tube with a valve at the bottom, termed the bailer) into the well then hoisting it out after the container fills.

**Beta radioactivity** Beta radiation is composed of a particle, consisting of an electron, spontaneously emitted from the nucleus of a subset of radioactive elements during radioactive decay. Beta radiation, like alpha radiation, is ionizing radiation—it strips electrons from adjacent atoms as it passes. Beta radiation can penetrate only the surface layer of skin; thus, a beta-particle emitting radionuclide must be ingested in order to contact internal organs or tissues. An accumulation of tissue damage in the cell nucleus may lead to cell mutation and potential cancer formation.

**Beta radioactivity, gross** A laboratory measurement of total beta radioactivity emitted by a sample. This measurement includes radioactivity emitted by naturally occurring progeny of uranium and thorium, such as radium-228 and lead-210, and numerous other naturally occurring beta-particle-emitting radioactive isotopes such as potassium, as well as a host of manmade radionuclides.

**Beta radioactivity count** An analytical technique that specifies total beta radioactivity emitted by a chemically purified sample that contains only one radionuclide of interest. The beta-particle activity is counted in a low-background gas proportional counter.

**C**

**Concentration Factor (CF)** The ratio of the initial feed flow rate relative to the final retentate flow rate.

**Contaminant** As defined in the Safe Drinking Water Act, any physical, chemical, biological, or radiological substance or matter in water.

**D**

**Decay product of radiation** The isotope remaining after radioactive decay.

**F**

**False negative** The analytical instrumentation records no radioactivity above the background level when radioactivity is present.

**False positive** The analytical instrumentation records radioactivity above the background level when no such radioactivity is present.

**Fission, nuclear** The splitting of an atomic nucleus into two smaller nuclear particles coupled with the release of one or more neutrons and nuclear energy.

**G**

**Gamma radioactivity** Gamma radiation is composed of packets of energy, also known as photons or photon particles, termed collectively as gamma rays, spontaneously emitted from the nucleus of most radioactive elements during radioactive decay. Gamma radiation is ionizing radiation meaning that it strips electrons from adjacent atoms as it passes. Gamma radiation can penetrate through skin into internal tissues as opposed to alpha and beta radiation, which cannot. An accumulation of tissue damage in the cell nucleus from gamma radiation may lead to cell mutation and potential cancer formation.

**H**

**Half-life** The interval of time required for exactly half the atoms of a given radionuclide to undergo radioactive decay.

**"Hot" particles** A subset of particles randomly dispersed in a population of particles that have rarely occurring (typically manmade) radionuclides attached to them.

**I**

**Isotope** Various forms of a single element differing in the number of neutrons in the

nucleus. Unstable isotopes of an element decay through the emission of a form of radioactivity.

**L**

**Laboratory reporting level (LRL)** The laboratory reporting level is a minimum concentration pre-determined by the laboratory personnel before the sample analysis begins; generally, it is based on typical counting results under routine analytical instrument operating conditions in a given sample matrix using known standards and blank samples (American Society for Testing Materials, 1999), which the laboratory personnel define as a level of detection they can routinely achieve. It is generally defined by the requirement that the counted radioactivity must differ from the background count by three to six times the standard deviation of the background count. The LRL was set at 0.1 pCi/L for the radionuclides in this study.

**M**

**Matrix effect** Analytical uncertainty or difficulty in quantifying the target analyte as a result of the composition or concentration of non-target compounds in the sample.

**Maximum contaminant level (MCL)** The maximum permissible level of a contaminant in water that is delivered to the free flowing outlet of the ultimate user of a public water-supply system. The MCL for radionuclides is an expression of the acceptable health risk of developing or dying from cancer per unit ingestion of water containing a harmful substance entering the body (exposure). The MCLs for Radium-226, Radium-228, uranium and gross alpha-particle activity in community water systems are as follows: (a) Sum of Radium-226 and Radium-228, 5 pCi/L, (b) Uranium, 30 microgram per liter, and (c) Gross alpha-particle activity (including Ra-226 but excluding radon and uranium), 15 pCi/L.

**Minimum detectable concentration, sample-specific (SSMDC)** The minimum quantity of a specific radionuclide detectable at potentially quantifiable level by the counting instrument for any given sample for a given analysis defined by instrument operating conditions, sample recovery, and variation in background radiation at the time of analysis. This value is computed individually for each radionuclide

analysis on the basis of instrument operating conditions at the time because of the variability in background radioactivity and instrument performance over time. For purposes of this report, the SSMDC generally will be referred to when a sample result is evaluated unless otherwise specified. The SSMDC differs from the LRL, in that it is specific to the individual sample, whereas the LRL is a pre-determined minimum concentration set by laboratory personnel before sample analysis begins that can be achieved routinely; it is generally based on typical results under routine operating conditions in a given matrix using known standards (American Society for Testing Materials, 1999). In most cases, the SSMDC is less than the LRL. In some cases, such as in a complex sample matrix, the SSMDC can exceed the LRL (because of matrix interference or effect, or other analytical complication).

## N

**Negative result** A result from a radiation measurement (count) of a sample over a fixed interval of time where the measured radioactivity from the sample is less than the long-term average background radiation reported routinely by the instrument. In practical terms, the result is less than the sample-specific minimum detectable concentration and indicates that radioactivity was not detected.

## P

**Picocurie per liter** A measurement unit that expresses the amount of radioactivity in water. One picocurie per liter (pCi/L) equals 2.2 radioactive disintegrations per minute per liter of water.

**Plutonium** Plutonium (Pu) is a manmade radioactive actinide element. It is not a normal part of rocks. Much soil, air, and water has been contaminated by release of Pu from nuclear weapons testing and other activities. Three important isotopes of Pu are Pu-239, Pu-240, and Pu-241.

**Precision estimate (P.E.) or uncertainty** A calculated measure of uncertainty of the laboratory analysis. Determination of the precision estimate for radionuclides includes the evaluation of many sources of error, some that are unique to radionuclides. Because radioactive elements decay randomly at any given instant of time, any measurement of radioactivity has

an associated uncertainty (also called “counting error”) independent of, and in addition to, laboratory sources of analytical uncertainty. In most circumstances, counting error decreases with increasing counting time. Uncertainty can be reported in a variety of ways; the most common are (1) the sum of the laboratory and counting uncertainty, known as the “precision estimate” or the “combined standard uncertainty (CSU)” (or less frequently as the “total propagated uncertainty”) and (2) a counting error or counting uncertainty only. There is a 67-percent or 95-percent probability (based on one or two standard deviations, respectively, of the radioactivity count) that the true value of the radionuclide concentration is within the range of the reported measured value plus or minus the precision estimate or uncertainty. The precision estimate or uncertainty values are generally smaller than the measured value except when the measured values are low concentrations (near the LRL). The precision estimates associated with the various radionuclide concentrations determined by the alpha spectrometry measurement technique and presented in this report are given as the two standard deviation (propagated) precision estimates.

## R

**Radionuclide** An isotope of an element that emits radiation.

**Targential-flow filtration:** Filtration technique where particles are moved by liquid flow across the filter surface rather than forced onto the surface of the filter material. The process minimizes colloid coagulation.

## T

**Thorium** Thorium is a naturally occurring radioactive actinide element.

**Tortuous path filtration** Filtration where the liquid is passed through a meshed media (usually encapsulated) with randomly occurring pathways designed to retain particles of greater diameter than that for which the filter is rated while passing the fluids and particles of smaller size than the rating.

## U

**Uranium** Uranium is a naturally occurring radioactive actinide element. It is a normal part of rocks, soil, air, and water. Natural uranium

is a mixture of three isotopes, U-234, U-235, and U-238. U-238 is by far the most common type of uranium on earth and is the least radioactive. U-234 is the most radioactive type of uranium. U-235 is used as a fuel in power plants and weapons. The amount of U-234 and U-235 in natural uranium is increased through the industrial process called enrichment. Uranium can react with tissues in the body and may damage the kidneys, as well as pose a radiation-induced cancer risk.

**Ultrafiltration** Filtration of particle sizes of 0.1 micron or smaller at high pressure.

## **W**

**Weapons-grade plutonium** Weapons-grade plutonium (Pu) is plutonium with less than 7 percent plutonium-240 content and usually less than 1 percent Pu-241 and Am-241 content. Weapons-grade Pu can be in a variety of chemical or physical forms. The weapon core (or pit) is composed primarily of the Pu-239 isotope enclosed within a casing material.

**Tables 7A–7B**

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**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.

[Data are sorted by well depth; mg/L, milligram per liter; pCi/L, picocurie per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; NTU, Nephelometric Turbidity Unit;  $\mu$ S/cm, microsiemens per centimeter at 25 degrees Celsius; BLS, below land surface; <, less than; K, thousand; NA, not applicable; --, no data. Number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number.]

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Quality-assurance data indicator <sup>2</sup> (code) (99911)	Plutonium -238 (pCi/L) (22012/22001)	Plutonium -238, 2 SIGMA P.E. (pCi/L) (61949/49939)	Plutonium -238, SSMDC (pCi/L)	Plutonium -239+240 (pCi/L) (49475/49940)	Plutonium -239+240, 2 SIGMA P.E. (pCi/L) (61950/49941)	Plutonium -239+240, SSMDC (pCi/L)
291377	R2 (NA)	2/7/2000	1017	1036	100	0	0.0042	0.00465	0	0.0042	0.00465
291377	R3 (NA)	2/7/2000	1104	1118	30	.00246	.00625	.0141	.00736	.00842	.0116
291377	0.45F (ULTRAFILTER, RETENTATE)	2/7/2000	1140	1225	30	0	.00316	.0035	.00206	.0038	.00729
291377	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/7/2000	1140	1229	30	-.00125	.00533	.0179	.00208	.00417	.00563
291370	R2 (NA)	2/11/2000	0926	1001	30	-.00166	.00237	.0143	-.00166	.00237	.0143
291370	R3 (NA)	2/11/2000	1022	1043	30	.00152	.00306	.00413	.00457	.00532	.00413
291370	0.45F (ULTRAFILTER, RETENTATE)	2/11/2000	1112	1216	--	-.000641	.00129	.00906	0	.00392	.00434
291370	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/11/2000	1112	1211	20	0	.00417	.00461	-.000681	.00137	.00962
291203	R2 (NA)	2/23/2000	0955	1033	30	-.00266	.00269	.0143	-.00464	.00358	.0174
291203	RT1 (NA)	2/23/2000	1053	1056	--	0	.00355	.00392	.00145	.0029	.00392
291203	RT2 (NA)	2/23/2000	1108	1111	--	0	.00421	.00466	.00103	.00371	.00972
291203	RT3 (NA)	2/23/2000	1115	1117	--	.0154	.01	.00416	-.000614	.00123	.00868
291203	RT4 (NA)	2/23/2000	1120	1122	--	-.00119	.00169	.0102	-.00236	.00238	.0127
291203	R3 (NA)	2/23/2000	1142	1324	100	-.00186	.00217	.0121	0	.0038	.00421
291203	0.45F (ULTRAFILTER, RETENTATE)	2/23/2000	1448	1714	--	0	.00442	.00489	-.000722	.00145	.0102
291203	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/23/2000	1449	1714	10	-.00163	.0019	.0106	-.00245	.00398	.0143
291203	0.45Fa (CAPSULE FILTER)	2/23/2000	1450	1658	100	.000373	.00428	.0128	0	.00456	.00504
291203	0.05F (SEQUENTIAL CAPSULE FILTERS)	2/23/2000	1451	1713	10	--	--	--	--	--	--
291371	R1 (NA)	12/8/1999	1103	1108	30	--	--	--	--	--	--
291371	R1 (NA)	12/8/1999	1112	1117	30	0	.00325	.00359	0	.00325	.00359

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

[Data are sorted by well depth; mg/L, milligram per liter; pCi/L, picocurie per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; NTU, Nephelometric Turbidity Unit;  $\mu$ S/cm, microsiemens per centimeter at 25 degrees Celsius; BLS, below land surface; <, less than; K, thousand; NA, not applicable; --, no data. Number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number.]

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Quality-assurance data indicator <sup>2</sup> (code) (99911)	Plutonium -238 (pCi/L) (22012/22001)	Plutonium -238, 2 SIGMA P.E. (pCi/L) (61949/49939)	Plutonium -238, SSMDC (pCi/L)	Plutonium -239+240 (pCi/L) (49475/49940)	Plutonium -239+240, 2 SIGMA P.E. (pCi/L) (61950/49941)	Plutonium -239+240, SSMDC (pCi/L)
291371	R2 (NA)	12/8/1999	1305	1310	30	0	0.00325	0.00359	0.000795	0.00286	0.00748
291371	R3 (NA)	12/8/1999	1451	1503	30	-.00151	.00214	.0129	.000376	.00432	.0129
291371	0.45F, (ULTRAFILTER, RETENTATE)	12/8/1999	1559	1630	30	0	.00326	.00361	-.000532	.00107	.00752
291371	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/8/1999	1559	1640	30	-.000532	.00107	.00752	0	.00326	.0036
291379	R2 (NA)	1/6/2000	0954	1034	100	.00494	.00679	.0107	0	.00465	.00514
291379	R3 (NA)	1/6/2000	1042	1106	--	.00124	.00249	.00336	0	.00304	.00336
291379	0.45F (ULTRAFILTER, RETENTATE)	1/6/2000	1155	1301	20	0	.00332	.00367	0	.00332	.00367
291379	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	1/6/2000	1155	1307	20	.00178	.00356	.00481	-.00142	.00202	.0122
291372	R2 (NA)	2/1/2000	1001	1030	100	0	.00344	.00381	0	.00344	.00381
291372	R3 (NA)	2/1/2000	1046	1108	20	-.00178	.00207	.0116	.000296	.0034	.0102
291372	0.45F (ULTRAFILTER, RETENTATE)	2/1/2000	1141	1234	--	0	.00413	.00457	.00505	.00588	.00456
291372	0.0029F (10K DALTON PERMEATE)	2/1/2000	1141	1239	--	-.00139	.00197	.0119	-.00138	.00197	.0119
291375	R2 (NA)	12/3/1999	1100	1200	--	0	.0063	.00698	-.00103	.0015	.0145
291375	R3 (NA)	12/3/1999	1334	1347	--	0	.0061	.00673	0	.0061	.00673
291375	0.45F (ULTRAFILTER, RETENTATE)	12/3/1999	1454	1507	20	-.0029	.0029	.0249	.00361	.011	.0266
291375	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/3/1999	1524	1613	20	0	.0067	.00745	0	.0067	.00744
291374	R2 (NA)	2/15/1999	1007	1054	30	-.00145	.00207	.0205	.0058	.0105	.0205
291374	R3 (NA)	2/15/1999	1055	1122	--	-.000533	.00107	.0128	0	.00652	.00721
291374	0.45F (ULTRAFILTER, RETENTATE)	2/15/1999	1150	1325	--	.00228	.00583	.0137	0	.00698	.00773
291374	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/1999	1150	1330	--	-.00194	.00226	.0204	.00323	.00647	.00874

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

[Data are sorted by well depth; mg/L, milligram per liter; pCi/L, picocurie per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; NTU, Nephelometric Turbidity Unit;  $\mu$ S/cm, microsiemens per centimeter at 25 degrees Celsius; BLS, below land surface; <, less than; K, thousand; NA, not applicable; --, no data. Number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number.]

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Quality-assurance data indicator <sup>2</sup> (code) (99911)	Plutonium -238 (pCi/L) (22012/22001)	Plutonium -238, 2 SIGMA P.E. (pCi/L) (61949/49939)	Plutonium -238, SSMDC (pCi/L)	Plutonium -239+240 (pCi/L) (49475/49940)	Plutonium -239+240, 2 SIGMA P.E. (pCi/L) (61950/49941)	Plutonium -239+240, SSMDC (pCi/L)
291376	R2 (NA)	2/15/2000	1012	1050	100	0.00959	0.0113	0.0187	0.00915	0.0101	0.015
291376	R3 (NA)	2/15/2000	1119	1207	30	-.00157	.00223	.0135	0	.0048	.00532
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1313	1518	100	0	.00445	.00492	-.000726	.00146	.0103
291376	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/2000	1314	1525	100	-.000755	.00107	.00648	-.000377	.000756	.00533
291376	0.05F (SEQUENTIAL CAPSULE FILTERS)	2/15/2000	1338	1500	--	--	--	--	--	--	--
291378	R1 (NA)	8/25/1999	1128	1137	30	-.00169	.00197	.011	.00	.00345	.00382
291378	R3 (NA)	8/25/1999	1640	1700	10	.0014	.0028	.00379	.0014	.0028	.00379
291378	0.45F (ULTRAFILTER, RETENTATE)	8/25/1999	1700	1810	--	-.000566	.0011	.008	.00142	.00284	.00384
291378	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	8/25/1999	1750	1810	--	.00147	.00295	.00398	-.000587	.00118	.0083

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Americium -241 (pCi/L) (29867)	Americium -241, 2 SIGMA P.E. (pCi/L) (49942)	Americium -241, SSMDC (pCi/L)	Uranium -238 (pCi/L) (22603)	Uranium -238, 2 SIGMA P.E. (pCi/L) (75991)	Uranium -238, SSMDC (pCi/L)	Uranium -234 (pCi/L) (22610)	Uranium -234, 2 SIGMA P.E. (pCi/L) (75992)
291377	R2 (NA)	2/7/2000	1017	1036	0.00319	0.00588	0.0113	0.0388	0.0271	0.0345	0.0848	0.0386
291377	R3 (NA)	2/7/2000	1104	1118	-0.000804	.00161	.0114	.045	.0345	.0536	.0507	.032
291377	0.45F (ULTRAFILTER, RETENTATE)	2/7/2000	1140	1225	-0.000797	.0016	.0113	.0743	.0413	.0444	.0286	.0262
291377	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/7/2000	1140	1229	0	.00407	.0122	.0536	.0345	.0329	.0526	.0345
291370	R2 (NA)	2/11/2000	0926	1001	.00539	.00743	.0117	.00822	.0134	.0257	.00971	.0176
291370	R3 (NA)	2/11/2000	1022	1043	-0.00083	.00167	.0117	.0191	.0181	.0191	.0119	.0164
291370	0.45F (ULTRAFILTER, RETENTATE)	2/11/2000	1112	1216	.00117	.00419	.011	.00727	.0146	.00315	.0113	.0167
291370	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/11/2000	1112	1211		.00419	.0125	.022	.025	.0444	.0102	.0177
291203	R2 (NA)	2/23/2000	0955	1033	.000393	.00452	.0135	.00193	.00752	.0179	.00578	.00932
291203	RT1 (NA)	2/23/2000	1053	1056	--	--	--	--	--	--	--	--
291203	RT2 (NA)	2/23/2000	1108	1111	--	--	--	--	--	--	--	--
291203	RT3 (NA)	2/23/2000	1115	1117	--	--	--	--	--	--	--	--
291203	RT4 (NA)	2/23/2000	1120	1122	--	--	--	--	--	--	--	--
291203	R3 (NA)	2/23/2000	1142	1324	.0159	.0114	.0119	.00729	.00808	.0119	.00971	.00874
291203	0.45F (ULTRAFILTER, RETENTATE)	2/23/2000	1448	1714	.000329	.00379	.0113	.0102	.00998	.0135	.0149	.0114
291203	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/23/2000	1449	1714	.00277	.00511	.00979	.00261	.00713	.016	.00373	.0082
291203	0.45Fa (CAPSULE FILTER)	2/23/2000	1450	1658	.00442	.00608	.00961	-.00103	.00439	.0147	.00925	.00957
291203	0.05F (SEQUENTIAL CAPSULE FILTERS)	2/23/2000	1451	1713	--	--	--	--	--	--	--	--
291371	R1 (NA)	12/8/1999	1103	1108	.00164	.00329	.00444	--	--	--	--	--
291371	R1 (NA)	12/8/1999	1112	1117	.0341	.0169	.00513	.00887	.0119	.022	.014	.0106

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Americium -241 (pCi/L) (29867)	Americium -241, 2 SIGMA P.E. (pCi/L) (49942)	Americium -241, SSMDC (pCi/L)	Uranium -238 (pCi/L) (22603)	Uranium -238, 2 SIGMA P.E. (pCi/L) (75991)	Uranium -238, SSMDC (pCi/L)	Uranium -234 (pCi/L) (22610)	Uranium -234, 2 SIGMA P.E. (pCi/L) (75992)
291371	R2 (NA)	12/8/1999	1305	1310	0.00462	0.00538	0.00417	0	0.00839	0.0213	0.0117	0.0113
291371	R3 (NA)	12/8/1999	1451	1503	.00724	.00724	.0089	.0106	.0101	.0142	.0124	.0108
291371	0.45F (ULTRAFILTER, RETENTATE)	12/8/1999	1559	1630	.0129	.00883	.00389	.00594	.0068	.00933	.00264	.00736
291371	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/8/1999	1559	1640	.0298	.014	.008	.0031	.00516	.00968	.00423	.00682
291379	R2 (NA)	1/6/2000	0954	1034	.00785	.00713	.00426	.0311	.0166	.0154	.0726	.0269
291379	R3 (NA)	1/6/2000	1042	1106	.00956	.00794	.00432	.0108	.0147	.0275	.00843	.0149
291379	0.45F (ULTRAFILTER, RETENTATE)	1/6/2000	1155	1301	.0156	.0101	.00422	.0121	.0144	.0259	.0136	.0111
291379	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	1/6/2000	1155	1307	.0355	.0155	.00401	.00404	.00912	.0193	.00625	.00878
291372	R2 (NA)	2/1/2000	1001	1030	-.00244	.00246	.0131	.00454	.00818	.0163	.00871	.0108
291372	R3 (NA)	2/1/2000	1046	1108	-.00129	.00184	.0111	.017	.013	.0175	.00495	.00958
291372	0.45F (ULTRAFILTER, RETENTATE)	2/1/2000	1141	1234	.00349	.00496	.00473	.00719	.00798	.0118	.00993	.0111
291372	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/1/2000	1141	1239	-.00182	.00213	.0119	.00175	.00681	.0162	.00663	.0117
291375	R2 (NA)	12/3/1999	1100	1200	-.00068	.0014	.0163	.00522	.0245	.0579	.00588	.0138
291375	R3 (NA)	12/3/1999	1334	1347	.00329	.0066	.00893	.00000	.00742	.0249	.0156	.0172
291375	0.45F (ULTRAFILTER, RETENTATE)	12/3/1999	1454	1507	0	.0083	.00915	.00265	.00993	.0259	.00795	.0138
291375	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/3/1999	1524	1613	.0103	.013	.0176	.00632	.0101	.0168	.0014	.00744
291374	R2 (NA)	12/15/1999	1007	1054	0	.00797	.00881	-.00001	.0406	.115	.0257	.0447
291374	R3 (NA)	12/15/1999	1055	1122	-.000701	.00141	.0168	.0037	.011	.0272	.00888	.0132
291374	0.45F (ULTRAFILTER, RETENTATE)	12/15/1999	1150	1325	.000678	.00731	.0233	.0276	.0226	.0299	.0262	.0212

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Americium -241 (pCi/L) (29867)	Americium -241, 2 SIGMA P.E. (pCi/L) (49942)	Americium -241, SSMDC (pCi/L)	Uranium -238 (pCi/L) (22603)	Uranium -238, 2 SIGMA P.E. (pCi/L) (75991)	Uranium -238, SSMDC (pCi/L)	Uranium -234 (pCi/L) (22610)	Uranium -234, 2 SIGMA P.E. (pCi/L) (75992)
291374	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/15/1999	1150	1330	0	0.00868	0.00961	0.0151	0.0199	0.0377	0.00144	0.00762
291376	R2 (NA)	2/15/2000	1012	1050	0.0016	.00321	.00433	.00854	.0101	.0167	.0144	.0123
291376	R3 (NA)	2/15/2000	1119	1207	-.00247	.0025	.0133	.00943	.00977	.015	.00873	.00985
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1313	1518	.00152	.00304	.00411	.00393	.0054	.00854	.0118	.00948
291376	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/2000	1314	1525	.00434	.00597	.00943	-.00356	.00323	.0165	.00356	.00782
291376	0.05F (SEQUENTIAL CAPSULE FILTERS)	2/15/2000	1338	1500	--	--	--	--	--	--	--	--
291378	R1 (NA)	8/25/1999	1128	1137	0	.00638	.00706	.0508	.0259	.0137	.0851	.0347
291378	R3 (NA)	8/25/1999	1640	--	-.00156	.00222	.0134	.0161	.016	.0198	.0336	.0242
291378	0.45F (ULTRAFILTER, RETENTATE)	8/25/1999	1700	--	.00111	.004	.0105	-.0155	.01864	.0582	.011	.0166
291378	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	8/25/1999	1750	1810	-.00128	.00182	.011	--	--	--	--	--

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Uranium -234, SSMDC (pCi/L)	Uranium -235 (pCi/L) (22620)	Uranium -235, 2 SIGMA P.E. (pCi/L) (75994)	Uranium -235, SSMDC (pCi/L)	Thorium -228 (pCi/L) (61738)	Thorium -228, SIGMA P.E. (pCi/L) (61739)	Thorium -228, SSMDC (pCi/L)	Thorium -230 (pCi/L) (26503)	Thorium -230, 2 SIGMA P.E. (pCi/L) (75997)
291377	R2 (NA)	2/7/2000	1017	1036	0.0295	0.0172	0.0182	0.028	--	--	--	--	--
291377	R3 (NA)	2/7/2000	1104	1118	.0352	-.00000145	.00897	.0301	--	--	--	--	--
291377	0.45F (ULTRAFILTER, RETENTATE)	2/7/2000	1140	1225	.0384	.017	.0182	.0214	--	--	--	--	--
291377	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/7/2000	1140	1229	.0352	.0067	.014	.0302	--	--	--	--	--
291370	R2 (NA)	2/11/2000	0926	1001	.0371	-.000748	.0015	.0179	--	--	--	--	--
291370	R3 (NA)	2/11/2000	1022	1043	.0293	.00716	.0114	.0191	--	--	--	--	--
291370	0.45F (ULTRAFILTER, RETENTATE)	2/11/2000	1112	1216	.0315	.000808	.0087	.0277	--	--	--	--	--
291370	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/11/2000	1112	1211	.0363	-.00508	.00423	.033	--	--	--	--	--
291203	R2 (NA)	2/23/2000	0955	1033	.0179	.00154	.00607	.015	--	--	--	--	--
291203	RT1 (NA)	2/23/2000	1053	1056	--	--	--	--	--	--	--	--	--
291203	RT2 (NA)	2/23/2000	1108	1111	--	--	--	--	--	--	--	--	--
291203	RT3 (NA)	2/23/2000	1115	1117	--	--	--	--	--	--	--	--	--
291203	RT4 (NA)	2/23/2000	1120	1122	--	--	--	--	--	--	--	--	--
291203	R3 (NA)	2/23/2000	1142	1324	.0098	.00139	.00547	.0135	--	--	--	--	--
291203	0.45F (ULTRAFILTER, RETENTATE)	2/23/2000	1448	1714	.0111	-.000392	.00477	.0153	--	--	--	--	--
291203	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/23/2000	1449	1714	.0173	.000373	.00454	.0146	--	--	--	--	--
291203	0.45Fa (CAPSULE FILTER)	2/23/2000	1450	1658	.0147	.00171	.00668	.0159	--	--	--	--	--
291203	0.05F (SEQUENTIAL CAPSULE FILTERS)	2/23/2000	1451	1713	--	--	--	--	--	--	--	--	--
291371	R1 (NA)	12/8/1999	1103	1108	--	--	--	--	--	--	--	--	--
291371	R1 (NA)	12/8/1999	1112	1117	.0117	-.00102	.00437	.0146	--	--	--	--	--

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Uranium -234, SSMDC (pCi/L)	Uranium -235 (pCi/L) (22620)	Uranium -235, 2 SIGMA P.E. (pCi/L) (75994)	Uranium -235, SSMDC (pCi/L)	Thorium -228 (pCi/L) (61738)	Thorium -228, SIGMA P.E. (pCi/L) (61739)	Thorium -228, SSMDC (pCi/L)	Thorium -230 (pCi/L) (26503)	Thorium -230, 2 SIGMA P.E. (pCi/L) (75997)
291371	R2 (NA)	12/8/1999	1305	1310	0.0176	-0.00213	0.00248	0.0138	--	--	--	--	--
291371	R3 (NA)	12/8/1999	1451	1503	.0142	.00656	.00751	.0103	--	--	--	--	--
291371	0.45F (ULTRAFILTER, RETENTATE)	12/8/1999	1559	1630	.0164	.00363	.00604	.0113	--	--	--	--	--
291371	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/8/1999	1559	1640	.0131	.00225	.00416	.00796	--	--	--	--	--
291379	R2 (NA)	1/6/2000	0954	1034	.0223	.0304	.0166	.0166	0.0302	0.0384	0.07	0.00531	0.0136
291379	R3 (NA)	1/6/2000	1042	1106	.0298	-.00442	.0061	.0221	.0201	.0332	.0684	.0218	.0237
291379	0.45F (ULTRAFILTER, RETENTATE)	1/6/2000	1155	1301	.013	.000756	.00614	.0162	.0339	.039	.0684	.0101	.0184
291379	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	1/6/2000	1155	1307	.0158	.00257	.00702	.0158	.00944	.0282	.0666	.00457	.0117
291372	R2 (NA)	2/1/2000	1001	1030	.0188	-.000757	.00152	.0107	.0715	.0496	.0661	.00947	.0152
291372	R3 (NA)	2/1/2000	1046	1108	.0195	.000707	.00575	.0152	.0284	.0342	.0632	.00969	.0139
291372	0.45F (ULTRAFILTER, RETENTATE)	2/1/2000	1141	1234	.0189	.00377	.00627	.0118	.055	.047	.0747	.0311	.0275
291372	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/1/2000	1141	1239	.0232	.00454	.00625	.00987	.0698	.0468	.055	.0053	.0107
291375	R2 (NA)	12/3/1999	1100	1200	.0314	-.000655	.00728	.0255	.0505	.054	.0984	.00955	.017
291375	R3 (NA)	12/3/1999	1334	1347	.0278	-.000678	.00136	.0162	.0587	.0608	.111	.00377	.013
291375	0.45F (ULTRAFILTER, RETENTATE)	12/3/1999	1454	1507	.0285	.000662	.00714	.0228	.0979	.0998	.181	.0261	.036
291375	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/3/1999	1524	1613	.0222	-.00422	.00351	.0274	.0609	.087	.174	.00649	.023
291374	R2 (NA)	12/15/1999	1007	1054	.0919	-.00642	.0246	.0919	-.0152	.158	.588	-.00544	.011
291374	R3 (NA)	12/15/1999	1055	1122	.0234	.00962	.0131	.0209	.114	.274	.653	.0697	.14
291374	0.45F (ULTRAFILTER, RETENTATE)	12/15/1999	1150	1325	.025	.0145	.0167	.0268	.0654	.216	.567	.067	.135

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Uranium -234, SSMDC (pCi/L)	Uranium -235 (pCi/L) (22620)	Uranium -235, 2 SIGMA P.E. (pCi/L) (75994)	Uranium -235, SSMDC (pCi/L)	Thorium -228 (pCi/L) (61738)	Thorium -228, SIGMA P.E. (pCi/L) (61739)	Thorium -228, SSMDC (pCi/L)	Thorium -230 (pCi/L) (26503)	Thorium -230, 2 SIGMA P.E. (pCi/L) (75997)
291374	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/15/1999	1150	1330	0.0227	-0.00648	0.00444	0.0322	-0.0644	0.0418	0.517	0.0606	0.133
291376	R2 (NA)	2/15/2000	1012	1050	.0167	-.00000097	.00649	.018	--	--	--	--	--
291376	R3 (NA)	2/15/2000	1119	1207	.0162	.0014	.00551	.0136	--	--	--	--	--
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1313	1518	.0118	-.00121	.00172	.0104	--	--	--	--	--
291376	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/2000	1314	1525	.0165	-.000356	.00433	.0139	--	--	--	--	--
291376	0.05F (SEQUENTIAL CAPSULE FILTERS)	2/15/2000	1338	1500	--	--	--	--	--	--	--	--	--
291378	R1 (NA)	8/25/1999	1128	1137	.0137	.00	.007	.00774	--	--	--	--	--
291378	R3 (NA)	8/25/1999	1640	1700	.0288	.0021	.00728	.0198	.0377	.0374	.0601	.0216	.0234
291378	0.45F (ULTRAFILTER, RETENTATE)	8/25/1999	1700	1810	.033	-.00582	.00398	.0289	-.00399	.0047	.042	0	.0157
291378	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	8/25/1999	1750	1810	--	--	--	--	--	--	--	--	--

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Thorium -230, SSMDC (pCi/L)	Thorium -232 (pCi/L) (75976)	Thorium -232, 2 SIGMA P.E. (pCi/L) (75999)	Thorium -232, SSMDC (pCi/L)	Gross alpha, residue procedure, as TH-230 (pCi/L) (04126)	Gross alpha, 2 SIGMA P.E. (pCi/L) (75987)	Gross beta, residue procedure, as CS-137 (pCi/L) (03515)	Beta, 2 SIGMA P.E. (pCi/L) (75989)	Turbidity, field (NTU) (61028)	Sediment, suspended (mg/L) (80154)
291377	R2 (NA)	2/7/2000	1017	1036	--	--	--	--	5.4	2.91	<4	4.28	0.24	--
291377	R3 (NA)	2/7/2000	1104	1118	--	--	--	--	3.41	2.53	6.13	4.45	.12	--
291377	0.45F (ULTRAFILTER, RETENTATE)	2/7/2000	1140	1225	--	--	--	--	4.69	2.8	<4	4.35	.1	--
291377	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/7/2000	1140	1229	--	--	--	--	4.86	2.8	<4	4.2	.1	--
291370	R2 (NA)	2/11/2000	0926	1001	--	--	--	--	5.21	2.78	<4	3.89	1.41	1.3
291370	R3 (NA)	2/11/2000	1022	1043	--	--	--	--	<3	2.25	<4	4.21	.43	
291370	0.45 (ULTRAFILTER, RETENTATE)	2/11/2000	1112	1216	--	--	--	--	3.04	2.36	6.77	4.12	.3	
291370	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/11/2000	1112	1211	--	--	--	--	5	2.75	4.52	4.02	.3	--
291203	R2 (NA)	2/23/2000	0955	1033	--	--	--	--	<3	1.78	<4	3.64	.75	.9
291203	RT1 (NA)	2/23/2000	1053	1056	--	--	--	--	--	--	--	--	10.8	--
291203	RT2 (NA)	2/23/2000	1108	1111	--	--	--	--	--	--	--	--	3.32	--
291203	RT3 (NA)	2/23/2000	1115	1117	--	--	--	--	--	--	--	--	2.29	--
291203	RT4 (NA)	2/23/2000	1120	1122	--	--	--	--	--	--	--	--	1.07	--
291203	R3 (NA)	2/23/2000	1142	1324	--	--	--	--	<3	2.06	<4	3.69	1.32	--
291203	0.45F (ULTRAFILTER, RETENTATE)	2/23/2000	1448	1714	--	--	--	--	<3	1.5	<4	3.67	1.12	--
291203	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/23/2000	1449	1714	--	--	--	--	<3	2.04	5.97	3.86	1.12	--
291203	0.45Fa (CAPSULE FILTER)	2/23/2000	1450	1658	--	--	--	--	<3	2.09	4.87	3.8	1.12	--

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Thorium -230, SSMDC (pCi/L)	Thorium -232 (pCi/L) (75976)	Thorium -232, 2 SIGMA P.E. (pCi/L) (75999)	Thorium -232, SSMDC (pCi/L)	Gross alpha, residue procedure, as TH-230 (pCi/L) (04126)	Gross alpha, 2 SIGMA P.E. (pCi/L) (75987)	Gross beta, residue procedure, as CS-137 (pCi/L) (03515)	Beta, 2 SIGMA P.E. (pCi/L) (75989)	Turbidity, field (NTU) (61028)	Sediment, suspended (mg/L) (80154)
291203	0.05F (SEQUENTIAL CAPSULE FILTER)	2/23/2000	1451	1713	--	--	--	--	--	--	--	--	1.12	--
291371	R1 (NA)	12/8/1999	1103	1108	--	--	--	--	--	--	--	--	13.4	--
291371	R1 (NA)	12/8/1999	1112	1117	--	--	--	--	--	--	--	--	8.02	--
291371	R2 (NA)	12/8/1999	1305	1310	--	--	--	--	--	--	--	--	6.93	--
291371	R3 (NA)	12/8/1999	1451	1503	--	--	--	--	--	--	--	--	3.08	--
291371	0.45F (ULTRAFILTER, RETENTATE)	12/8/1999	1559	1630	--	--	--	--	--	--	--	--	1.06	--
291371	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/8/1999	1559	1640	--	--	--	--	--	--	--	--	1.06	--
291379	R2 (NA)	1/6/2000	0954	1034	0.0318	0	0.0163	0.018	<3	1.83	<4	3.83	3.48	4
291379	R3 (NA)	1/6/2000	1042	1106	.0275	-.00115	.00231	.0275	<3	1.79	<4	4.05	1.66	--
291379	0.45F (ULTRAFILTER, RETENTATE)	1/6/2000	1155	1301	.0357	-.00252	.00362	.0357	<3	1.78	<4	3.76	.59	--
291379	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	1/6/2000	1155	1307	.0274	.00457	.0117	.0274	<3	1.52	<4	3.72	.59	--
291372	R2 (NA)	2/1/2000	1001	1030	.0252	0	.0129	.0143	<3	1.99	<4	3.97	.73	.5
291372	R3 (NA)	2/1/2000	1046	1108	.0131	0	.0119	.0131	<3	2.05	4.09	4.11	.59	--
291372	0.45F (ULTRAFILTER, RETENTATE)	2/1/2000	1141	1234	.0257	.00215	.0114	.0339	<3	1.86	<4	3.9	.63	--
291372	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/1/2000	1141	1239	.0144	.00424	.0109	.0254	<3	2.12	<4	3.91	.63	--
291375	R2 (NA)	12/3/1999	1100	1200	.0338	-.00119	.0024	.0286	<3	2.29	<4	4.09	2.2	.7
291375	R3 (NA)	12/3/1999	1334	1347	.0356	-.00126	.0025	.0301	<3	2.13	<4	4.08	0.21	--

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Thorium -230, SSMDC (pCi/L)	Thorium -232 (pCi/L) (75976)	Thorium -232, 2 SIGMA P.E. (pCi/L) (75999)	Thorium -232, SSMDC (pCi/L)	Gross alpha, residue procedure, as TH-230 (pCi/L) (04126)	Gross alpha, 2 SIGMA P.E. (pCi/L) (75987)	Gross beta, residue procedure, as CS-137 (pCi/L) (03515)	Beta, 2 SIGMA P.E. (pCi/L) (75989)	Turbidity, field (NTU) (61028)	Sediment, suspended (mg/L) (80154)
291375	0.45F (ULTRAFILTER, RETENTATE)	12/3/1999	1454	1507	0.0568	-0.00201	0.0041	0.0481	<3	1.94	<4	3.87	0.76	--
291375	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/3/1999	1524	1613	.0612	-.00217	.0044	.0518	<3	2.28	<4	3.94	.3	--
291374	R2 (NA)	12/15/1999	1007	1054	.273	.0678	.137	.184	<3	1.87	<4	4.01	.84	.8
291374	R3 (NA)	12/15/1999	1055	1122	.189	-.00558	.0112	.281	<3	2.06	<4	3.93	.46	--
291374	0.45F (ULTRAFILTER, RETENTATE)	12/15/1999	1150	1325	.182	.067	.135	.182	<3	1.78	<4	3.98	.28	--
291374	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/15/1999	1150	1330	.265	-.00528	.0106	.265	<3	1.84	<4	3.89	.28	--
291376	R2 (NA)	2/15/2000	1012	1050	--	--	--	--	<3	2.04	<4	3.94	1.44	.8
291376	R3 (NA)	2/15/2000	1119	1207	--	--	--	--	<3	2.31	<4	3.93	.67	--
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1313	1518	--	--	--	--	<3	1.85	<4	3.88	.54	--
291376	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/2000	1314	1525	--	--	--	--	<3	2.14	<4	3.99	.54	--
291376	0.05F (SEQUENTIAL CAPSULE FILTERS)	2/15/2000	1338	1500	--	--	--	--	--	--	--	--	0.54	--
291378	R1 (NA)	8/25/1999	1128	1137	--	--	--	--	--	--	--	--	38	--
291378	R3 (NA)	8/25/1999	1640	--	.0273	.0285	.0264	.0154	<3	2.28	<4	4.04	16.5	--
291378	0.45F (ULTRAFILTER, RETENTATE)	8/25/1999	1700	--	.0173	0	.0157	.0173	<3	2	<4	4.05	16.3	--
291378	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	8/25/1999	1750	1810	--	--	--	--	--	--	--	--	18.3	--

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Water level (depth BLS in feet) (72019)	Water temperature (degrees Celsius) (00010)	Field specific conductance (uS/cm at 25° C) (00095)	Oxygen dissolved (mg/L) (00300)	pH, field (standard units) (00400)
291377	R2 (NA)	2/7/2000	1017	1036	23.77	14.2	76	4.5	4.47
291377	R3 (NA)	2/7/2000	1104	1118	23.94	14.3	75	4.5	4.58
291377	0.45F (ULTRAFILTER, RETENTATE)	2/7/2000	1140	1225	--	14.5	75	4.6	4.61
291377	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/7/2000	1140	1229	--	14.5	75	4.6	4.61
291370	R2 (NA)	2/11/2000	0926	1001	31.60	15.5	57	--	4.77
291370	R3 (NA)	2/11/2000	1022	1043	--	16	58	9.45	4.7
291370	0.45F (ULTRAFILTER, RETENTATE)	2/11/2000	1112	1216	31.61	16	58	--	4.7
291370	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/11/2000	1112	1211	31.61	16	58	--	4.7
291203	R2 (NA)	2/23/2000	0955	1033	38.76	17.3	62.1	--	5.4
291203	RT1 (NA)	2/23/2000	1053	1056	--	20.1	56.3	--	5.48
291203	RT2 (NA)	2/23/2000	1108	1111	39.07	17.7	54.9	--	5.5
291203	RT3 (NA)	2/23/2000	1115	1117	--	17.4	54.4	--	5.44
291203	RT4 (NA)	2/23/2000	1120	1122	--	17.3	52.9	--	5.45
291203	R3 (NA)	2/23/2000	1142	1324	--	17.3	52	--	5.41
291203	0.45F (ULTRAFILTER, RETENTATE)	2/23/2000	1448	1714	--	18.2	53	10.1	5.39
291203	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/23/2000	1449	1714	--	18.2	53	--	5.4
291203	0.45Fa (CAPSULE FILTER)	2/23/2000	1450	1658	--	18.2	53	--	5.39
291203	0.05F (SEQUENTIAL CAPSULE FILTERS)	2/23/2000	1451	1713	--	18.2	53	--	5.39
291371	R1 (NA)	12/8/1999	1103	1108	--	16.6	112	--	4.96
291371	R1 (NA)	12/8/1999	1112	1117	39.05	16.5	114	10.5	5.18

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Water level (depth BLS in feet) (72019)	Water temperature (degrees Celsius) (00010)	Field specific conductance (uS/cm at 25° C) (00095)	Oxygen dissolved (mg/L) (00300)	pH, field (standard units) (00400)
291371	R2 (NA)	12/8/1999	1305	1310	--	17.6	114	--	5.34
291371	R3 (NA)	12/8/1999	1451	1503	--	16.9	116	--	5.38
291371	0.45F (ULTRAFILTER, RETENTATE)	12/8/1999	1559	1630	--	17.1	117	--	5.37
291372	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/1/2000	1141	1239	44.28	10.9	49	--	4.8
291375	R2 (NA)	12/3/1999	1100	1200	47.67	17	47	--	5.01
291375	R3 (NA)	12/3/1999	1334	1347		16.5	46	--	5.1
291375	0.45F (ULTRAFILTER, RETENTATE)	12/3/1999	1454	1507	47.7	16.5	46	--	5.1
291375	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/3/1999	1524	1613	--	16.5	54.3	--	4.67
291374	R2 (NA)	12/15/1999	1007	1054	53.35	17.5	52	--	5.64
291374	R3 (NA)	12/15/1999	1055	1122	53.33	17.2	52	9.3	5.73
291374	0.45F (ULTRAFILTER, RETENTATE)	12/15/1999	1150	1325	--	17.2	53	--	5.67
291374	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/15/1999	1150	1330	53.36	17.2	53	--	5.67
291376	R2 (NA)	2/15/2000	1012	1050	21.73	14.4	80	--	5.22
291376	R3 (NA)	2/15/2000	1119	1207	21.79	15.4	79.1	9.6	5.35
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1313	1518	21.74	15.1	79.6	--	5.38
291376	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/2000	1314	1525	--	15.1	79.6	--	5.38
291376	0.05F (SEQUENTIAL CAPSULE FILTERS)	2/15/2000	1338	1500	--	15.1	79.6	--	5.38
291378	R1 (NA)	8/25/1999	1128	1137	14.4	17	46	--	6.1
291378	R3 (NA)	8/25/1999	1640	--	--	15.5	44	---	5.91

**Table 7A.** Concentrations of radionuclides in filtered and unfiltered samples of water from observation wells and properties measured in the field, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Water level (depth BLS in feet) (72019)	Water temperature (degrees Celsius) (00010)	Field specific conductance (uS/cm at 25° C) (00095)	Oxygen dissolved (mg/L) (00300)	pH, field (standard units) (00400)
291378	0.45F (ULTRAFILTER, RETENTATE)	8/25/1999	1700	--	--	15.5	44	--	5.91
291378	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	8/25/1999	1750	1810	--	16	43	--	5.9

<sup>1</sup> Sample designation: R1, unfiltered, initial; R2, unfiltered, turbidity generally less than 10 NTU and slowly decreasing; RTi unfiltered, turbidity not stable and variable; R3, unfiltered, turbidity stable and generally less than 5 NTU; 0.45Fa, filtered, 45-micron filter; 0.45F, filtered with 45-micron capsule filter and from retentate port from 0.0029-micron ultrafilter, F0.0029, filtered sequentially through 0.45 micron capsule filter and 0.0029-micron ultrafilter; F0.05, filtered sequentially through 0.45-micron and 0.05-micron capsule filters.

<sup>2</sup> Associated quality-assurance data indicator code: 10, field or laboratory equipment blank; 10, concurrent duplicate; 30, sequential replicate; 100, multiple types.

**Table 7B.** Concentrations of radionuclides in filtered and unfiltered concurrent laboratory duplicate and sequential replicate samples of water from observation wells and equipment blank, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.

[Data are sorted by well depth; pCi/L, picocurie per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; <, less than; K, thousand; NA, not applicable; --, no data; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number.]

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Same medium (code) <sup>2</sup>	Replicate, type <sup>3</sup> (code) (99912)	Plutonium -238 (pCi/L) (22012/22001)	Plutonium -238, 2 SIGMA P.E. (pCi/L) (61949/49939)	Plutonium -238, SSMDC (pCi/L)	Plutonium -239+240 (pCi/L) (49475/49940)	Plutonium -239+240, 2 SIGMA P.E. (pCi/L) (61950/49941)	Plutonium -239+240, SSMDC (pCi/L)
291377	R2 (NA)	2/7/2000	1017	1036	S	10	--	--	--	--	--	--
291377	R2 (NA)	2/7/2000	1019	1028	S	20	0.00146	0.00293	0.00395	0.00292	0.00415	0.00395
291377	R2 (NA)	2/7/2000	1019	1028	S	20	-0.00041	.00498	.016	-0.000817	.00164	.0115
291377	R3 (NA)	2/7/2000	1104	1118	S	20	-0.00079	.00158	.0112	-0.00158	.00224	.0135
291377	0.45F (ULTRAFILTER, RETENTATE)	2/7/2000	1140	1225	S	20	-0.00042	.00514	.0165	0	.00518	.00573
291377	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/7/2000	1140	1229	S	20	-0.00193	.00225	.0126	.000965	.00347	.00909
291370	R2 (NA)	2/11/2000	0931	0946	S	20	-0.000786	.00158	.0111	-0.000786	.00158	.0111
291370	R2 (NA)	2/11/2000	0931	0946	S	20	-0.00201	.00235	.0131	-0.00134	.00191	.0115
291370	R3 (NA)	2/11/2000	1022	1043	S	20	.00215	.00432	.00584	0	.00527	.00583
291370	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/11/2000	1112	1211	6	10	-0.00166	.00236	.0142	0	.00507	.00561
291203	R2 (NA)	2/23/2000	0959	1017	S	20	0	.00347	.00384	-0.000566	.00114	.008
291203	R3 (NA)	2/23/2000	1143	1323	S	10	.0046	.0126	.0282	.00394	.01	.0226
291203	0.45Fa (CAPSULE FILTER BLANK)	2/17/2000	1553	1625	Q	10	.000404	.00492	.0158	--	--	--
291371	R1 (NA)	12/8/1999	1124	1128	S	20	.000372	.00754	.0195	-0.000743	.00149	.0105
291371	R1 (NA)	12/8/1999	1137	1140	S	20	.000811	.00292	.00764	-0.000541	.00108	.00764
291371	R2 (NA)	12/8/1999	1323	1341	S	20	.00168	.00337	.00455	-0.000672	.00135	.00949
291371	R3 (NA)	12/8/1999	1507	1521	S	20	-0.0021	.00245	.0137	.00175	.00352	.00475
291371	0.45F (ULTRAFILTER, RETENTATE)	12/8/1999	1640	1712	S	20	.00775	.00644	.0035	-0.00103	.00147	.00887
291371	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/8/1999	1640	1720	S	20	-0.000561	.00113	.00792	0	.00343	.0038
291371	0.45F (ULTRAFILTER, RETENTATE)	12/8/1999	1720	--	S	20	--	--	--	--	--	--

**Table 7B.** Concentrations of radionuclides in filtered and unfiltered concurrent laboratory duplicate and sequential replicate samples of water from observation wells and equipment blank, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

[Data are sorted by well depth; pCi/L, picocurie per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; <, less than; K, thousand; NA, not applicable; --, no data; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number.]

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Same medium (code) <sup>2</sup>	Replicate, type <sup>3</sup> (code) (99912)	Plutonium -238 (pCi/L) (22012/22001)	Plutonium -238, 2 SIGMA P.E. (pCi/L) (61949/49939)	Plutonium -238, SSMDC (pCi/L)	Plutonium -239+240 (pCi/L) (49475/49940)	Plutonium -239+240, 2 SIGMA P.E. (pCi/L) (61950/49941)	Plutonium -239+240, SSMDC (pCi/L)
291371	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/8/1999	1721	--	S	20	--	--	--	--	--	--
291379	R2 (NA)	1/6/2000	1011	1019	S	20	0	0.0069	0.00763	-0.000563	0.00113	0.0135
291379	R2 (NA)	1/6/2000	1011	1019	S	10	-0.00056	.00112	.0134	0	.00685	.00758
291379	0.45F (ULTRAFILTER, RETENTATE)	1/6/2000	1155	1301	S	10	--	--	--	--	--	--
291379	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE), LAB DUPLICATE	1/6/2000	1155	1307	S	10	0	.00326	.0036	0	.00326	.0036
291372	R2 (NA)	2/1/2000	1015	1022	S	20	0	.00386	.00428	0	.00386	.00427
291372	R2 (NA)	2/1/2000	1015	1022	S	10	--	--	--	--	--	--
291372	R3 (NA)	2/1/2000	1046	1108	S	10	--	--	--	--	--	--
291375	0.45F (ULTRAFILTER, RETENTATE)	12/3/1999	1454	1507	S	10	--	--	--	0	.0065	.00725
291375	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/3/1999	1524	1613	S	10	--	--	--	--	--	--
291374	R2 (NA)	2/15/1999	1008	1055	S	20	0	.00686	.00759	.00224	.00572	.0134
291376	R2 (NA)	2/15/2000	1016	1036	S	20	0	.00574	.00635	-.000936	.00188	.0132
291376	R2 (NA)	2/15/2000	1016	1036	S	10	--	--	--	--	--	--
291376	R3 (NA)	2/15/2000	1120	1208	S	20	-.000398	.00483	.0155	0	.00486	.00538
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1315	1518	S	20	-.00288	.00292	.0155	-.00072	.00144	.0102
291376	0.45F (ULTRAFILTER RETENTATE)	2/15/2000	1315	1518	S	10	--	--	--	--	--	--
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1537	1626	S	20	-.000729	.00146	.0103	.00182	.00365	.00494
291376	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/2000	1538	1642	S	20	0	.00389	.00431	0	.00389	.0043
291376	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/2000	1538	1642	S	10	0	.00435	.00481	-.00071	.00142	.01
291378	R1 (NA)	8/25/1999	1143	1151	S	20	0	.00338	.00374	-.00165	.00192	.0108

**Table 7B.** Concentrations of radionuclides in filtered and unfiltered concurrent laboratory duplicate and sequential replicate samples of water from observation wells and equipment blank, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

[Data are sorted by well depth; pCi/L, picocurie per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; <, less than; K, thousand; NA, not applicable; --, no data; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number.]

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Americium -241 (pCi/L) (29867)	Americium -241, 2 SIGMA P.E. (pCi/L) (49942)	Americium -241, SSMDC (pCi/L)	Uranium -238 (pCi/L) (22603)	Uranium -238, 2 SIGMA P.E. (pCi/L) (75991)	Uranium -238, SSMDC (pCi/L)	Uranium -234 (pCi/L) (22610)	Uranium -234, 2 SIGMA P.E. (pCi/L) (75992)
291377	R2 (NA)	2/7/2000	1017	1036	--	--	--	0.0478	0.029	0.0307	0.02	0.0195
291377	R2 (NA)	2/7/2000	1019	1028	--	--	--	--	--	--	--	--
291377	R2 (NA)	2/7/2000	1019	1028	--	--	--	--	--	--	--	--
291377	R3 (NA)	2/7/2000	1104	1118	--	--	--	--	--	--	--	--
291377	0.45F (ULTRAFILTER, RETENTATE)	2/7/2000	1140	1225	--	--	--	--	--	--	--	--
291377	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/7/2000	1140	1229	0.000354	--	--	--	--	--	--	--
291370	R2 (NA)	2/11/2000	0931	0946	--	--	--	--	--	--	--	--
291370	R2 (NA)	2/11/2000	0931	0946	--	--	--	--	--	--	--	--
291370	R3 (NA)	2/11/2000	1022	1043	--	--	--	--	--	--	--	--
291370	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/11/2000	1112	1211	.000365	--	--	--	--	--	--	--
291203	R2 (NA)	2/23/2000	0959	1017	-.00234	.00237	.0126	--	--	--	--	--
291203	R3 (NA)	2/23/2000	1143	1323	.0059	.00829	.0149	.0076	.00898	.0148	.00587	.00826
291203	0.45Fa (CAPSULE FILTER; BLANK)	2/17/2000	1553	1625	.00372	.0053	.00505	--	--	--	--	--
291371	R1 (NA)	12/8/1999	1124	1128	.0121	.00958	.0124	.0139	.0145	.0252	.0201	.0129
291371	R1 (NA)	12/8/1999	1137	1140	.0149	.00967	.00403	.0174	.0156	.0254	.00853	.0137
291371	R2 (NA)	12/8/1999	1323	1341	.00309	.00439	.00418	.0167	.0134	.019	.000724	.00588
291371	R3 (NA)	12/8/1999	1507	1521	.0031	.00442	.00421	.00711	.00814	.0112	.00316	.00881
291371	0.45F (ULTRAFILTER, RETENTATE)	12/8/1999	1640	1712	.127	.0337	.00836	0	.00817	.0207	.00621	.00916
291371	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/8/1999	1640	1720	.0513	.0195	.00863	.00455	.0082	.0163	.0072	.00895

**Table 7B.** Concentrations of radionuclides in filtered and unfiltered concurrent laboratory duplicate and sequential replicate samples of water from observation wells and equipment blank, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

[Data are sorted by well depth; pCi/L, picocurie per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; <, less than; K, thousand; NA, not applicable; --, no data; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number.]

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/ day/year)	Begin sample collection, time	End sample collection, time	Americium		Americium -241, SSMDC (pCi/L)	Uranium -238 (pCi/L) (22603)	Uranium		Uranium -234 (pCi/L) (22610)	Uranium -234, 2 SIGMA P.E. (pCi/L) (75992)
					Americium -241 (pCi/L) (29867)	Americium -241, 2 SIGMA P.E. (pCi/L) (49942)			Uranium -238, 2 SIGMA P.E. (pCi/L) (75991)	Uranium -238, SSMDC (pCi/L)		
291371	0.45F (ULTRAFILTER, RETENTATE)	12/8/1999	1720	--	0.00148	0.00584	0.0145	--	--	--	--	--
291371	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/8/1999	1721	--	.00202	.00406	.00549	--	--	--	--	--
291379	R2 (NA)	1/6/2000	1011	1019	0	.00742	.00821	--	--	--	--	--
291379	R2 (NA)	1/6/2000	1011	1019	0	.00748	.00828	--	--	--	--	--
291379	0.45F (ULTRAFILTER, RETENTATE)	1/6/2000	1155	1301	-.000681	.00137	.00962	0.00289	0.0105	0.0238	0.0116	0.0143
291379	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	1/6/2000	1155	1307	--	--	--	--	--	--	--	--
291372	R2 (NA)	2/1/2000	1015	1022	0	.00372	.00411	--	--	--	--	--
291372	R2 (NA)	2/1/2000	1015	1022	.00248	.00678	.0153	--	--	--	--	--
291372	R3 (NA)	2/1/2000	1046	1108	.00323	.00648	.00876	.0125	.0175	.0332	.013	.0152
29375	045F (ULTRAFILTER, RETENTATE)	12/3/1999	1454	1507	.00344	.0069	.00933	--	--	--	--	--
291375	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/3/1999	1524	1613	--	--	--	-.00361	.00328	.0266	.00505	.0105
291374	R2 (NA)	12/15/1999	1008	1055	.00326	.00654	.00884	--	--	--	--	--
291376	R2 (NA)	2/15/2000	1016	1036	.00132	.00519	.0129	--	--	--	--	--
291376	R2 (NA)	2/15/2000	1016	1036	.00192	.00384	.00519	--	--	--	--	--
291376	R3 (NA)	2/15/2000	1120	1208	-.000672	.00135	.00949	.015	.0102	.00884	.00907	.00867
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1315	1518	.00615	.00703	.00965	.0134	.0109	.0128	.00371	.00816
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1315	1518	--	--	--	0	.00605	.0168	.00905	.0102

**Table 7B.** Concentrations of radionuclides in filtered and unfiltered concurrent laboratory duplicate and sequential replicate samples of water from observation wells and equipment blank, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

[Data are sorted by well depth; pCi/L, picocurie per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; <, less than; K, thousand; NA, not applicable; --, no data; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number.]

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/ day/year)	Begin sample collection, time	End sample collection, time	Americium		Americium -241, SSMDC (pCi/L)	Uranium -238 (pCi/L) (22603)	Uranium		Uranium -234 (pCi/L) (22610)	Uranium	
					Americium -241 (pCi/L) (29867)	-241, 2 SIGMA P.E. (pCi/L) (49942)			-238, 2 SIGMA P.E. (pCi/L) (75991)	-234, SSMDC (pCi/L)		-234, 2 SIGMA P.E. (pCi/L) (75992)	
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1537	1626	0.00104	0.00375	0.00984	0.00346	0.00476	0.00751	0.0117	0.00879	
291376	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/2000	1538	1642	-0.00183	.00214	.0119	.000345	.00397	.0119	.00898	.00879	
291376	.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/2000	1538	1642	--	--	--	--	--	--	--	--	--
291378	R1 (NA)	8/25/1999	1143	1151	0	.00824	.00912	.0526	.0247	.00678	.0841	.0328	

**Table 7B.** Concentrations of radionuclides in filtered and unfiltered concurrent laboratory duplicate and sequential replicate samples of water from observation wells and equipment blank, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

[Data are sorted by well depth; pCi/L, picocurie per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; <, less than; K, thousand; NA, not applicable; --, no data; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number.]

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Uranium -234, SSMDC (pCi/L)	Uranium -235 (pCi/L) (22620)	Uranium -235, 2 SIGMA P.E. (pCi/L) (75994)	Uranium -235, SSMDC (pCi/L)	Thorium -228 (pCi/L) (61738)	Thorium -228, SIGMA P.E. (pCi/L) (61739)	Thorium -228, SSMDC (pCi/L)	Thorium -230 (pCi/L) (26503)	Thorium -230, 2 SIGMA P.E. (pCi/L) (75997)
291377	R2 (NA)	2/7/2000	1017	1036	0.0293	-0.000714	0.00143	0.0171	--	--	--	--	--
291377	R2 (NA)	2/7/2000	1019	1028	--	--	--	--	--	--	--	--	--
291377	R2 (NA)	2/7/2000	1019	1028	--	--	--	--	--	--	--	--	--
291377	R3 (NA)	2/7/2000	1104	1118	--	--	--	--	--	--	--	--	--
291377	0.45F (ULTRAFILTER, RETENTATE)	2/7/2000	1140	1225	--	--	--	--	--	--	--	--	--
291377	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/7/2000	1140	1229	--	--	--	--	--	--	--	--	--
291370	R2 (NA)	2/11/2000	0931	0946	--	--	--	--	--	--	--	--	--
291370	R2 (NA)	2/11/2000	0931	0946	--	--	--	--	--	--	--	--	--
291370	R3 (NA)	2/11/2000	1022	1043	--	--	--	--	--	--	--	--	--
291370	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/11/2000	1112	1211	--	--	--	--	--	--	--	--	--
291203	R2 (NA)	2/23/2000	0959	1017	--	--	--	--	--	--	--	--	--
291203	R3 (NA)	2/23/2000	1143	1323	.0148	.00518	.00836	.016	--	--	--	--	--
291203	0.45Fa (CAPSULE FILTER, BLANK)	2/17/2000	1551	1625	--	--	--	--	--	--	--	--	--
291371	R1 (NA)	12/8/1999	1124	1128	.0133	.00374	.00844	.0178	--	--	--	--	--
291371	R1 (NA)	12/8/1999	1137	1140	.0268	.00408	.00919	.0194	--	--	--	--	--
291371	R2 (NA)	12/8/1999	1323	1341	.0156	.00326	.00677	.0141	--	--	--	--	--
291371	R3 (NA)	12/8/1999	1507	1521	.0196	-.00158	.00225	.0136	--	--	--	--	--
291371	0.45F (ULTRAFILTER, RETENTATE)	12/8/1999	1640	1712	.0171	-.000346	.0042	.0135	--	--	--	--	--
291371	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/8/1999	1640	1720	.0148	.00227	.00579	.013	--	--	--	--	--

**Table 7B.** Concentrations of radionuclides in filtered and unfiltered concurrent laboratory duplicate and sequential replicate samples of water from observation wells and equipment blank, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

[Data are sorted by well depth; pCi/L, picocurie per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; <, less than; K, thousand; NA, not applicable; --, no data; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number.]

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Uranium -234, SSMDC (pCi/L)	Uranium -235 (pCi/L) (22620)	Uranium -235, 2 SIGMA P.E. (pCi/L) (75994)	Uranium -235, SSMDC (pCi/L)	Thorium -228 (pCi/L) (61738)	Thorium -228, SIGMA P.E. (pCi/L) (61739)	Thorium -228, SSMDC (pCi/L)	Thorium -230 (pCi/L) (26503)	Thorium -230, 2 SIGMA P.E. (pCi/L) (75997)
291371	0.45F (ULTRAFILTER, RETENTATE)	12/8/1999	1720	--	--	--	--	--	--	--	--	--	--
291371	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/8/1999	1721	--	--	--	--	--	--	--	--	--	--
291379	R2 (NA)	1/6/2000	1011	1019	--	--	--	--	--	--	--	--	--
291379	R2 (NA)	1/6/2000	1011	1019	--	--	--	--	--	--	--	--	--
291379	0.45F (ULTRAFILTER, RETENTATE)	1/6/2000	1155	1301	0.0257	0.000825	0.00671	0.0177	--	--	--	--	--
291379	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	1/6/2000	1155	1307	--	--	--	--	--	--	--	--	--
291372	R2 (NA)	2/1/2000	1015	1022	--	--	--	--	--	--	--	--	--
291372	R2 (NA)	2/1/2000	1015	1022	--	--	--	--	--	--	--	--	--
291372	R3 (NA)	2/1/2000	1046	1108	.027	-.00167	.00739	.0219	--	--	--	--	--
291375	0.45F (ULTRAFILTER, RETENTATE)	12/3/1999	1454	1507	--	--	--	--	--	--	--	--	--
291375	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/3/1999	1524	1613	.0228	.00577	.0104	.0204	--	--	--	--	--
291374	R2 (NA)	12/15/1999	1008	1055	--	--	--	--	--	--	--	--	--
291376	R2 (NA)	2/15/2000	1016	1036	---	--	--	--	--	--	--	--	--
291376	R2 (NA)	2/15/2000	1016	1036	--	--	--	--	--	--	--	--	--
291376	R3 (NA)	2/15/2000	1120	1208	.0122	.00188	.00477	.0107	--	--	--	--	--
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1315	1518	.0172	-.00111	.00476	.016	--	--	--	--	--
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1315	1518	.0168	.00181	.00706	.0168	--	--	--	--	--

**Table 7B.** Concentrations of radionuclides in filtered and unfiltered concurrent laboratory duplicate and sequential replicate samples of water from observation wells and equipment blank, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

[Data are sorted by well depth; pCi/L, picocurie per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; <, less than; K, thousand; NA, not applicable; --, no data; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number.]

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Uranium -234, SSMDC (pCi/L)	Uranium -235 (pCi/L) (22620)	Uranium -235, 2 SIGMA P.E. (pCi/L) (75994)	Uranium -235, SSMDC (pCi/L)	Thorium -228 (pCi/L) (61738)	Thorium -228, SIGMA P.E. (pCi/L) (61739)	Thorium -228, SSMDC (pCi/L)	Thorium -230 (pCi/L) (26503)	Thorium -230, 2 SIGMA P.E. (pCi/L) (75997)
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1537	1626	0.0104	-0.00106	0.00151	0.00913	--	--	--	--	--
291376	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/2000	1538	1642	.0119	.00587	.00825	.0148	--	--	--	--	--
291376	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/2000	1538	1642	--	--	--	--	--	--	--	--	--
291378	R1 (NA)	8/25/1999	1143	1151	.0141	-.001	.00143	.0141	--	--	--	--	--

**Table 7B.** Concentrations of radionuclides in filtered and unfiltered concurrent laboratory duplicate and sequential replicate samples of water from observation wells and equipment blank, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

[Data are sorted by well depth; pCi/L, picocurie per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; <, less than; K, thousand; NA, not applicable; --, no data; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number.]

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Thorium -230, SSMDC (pCi/L)	Thorium -232 (pCi/L) (75976)	Thorium -232, 2 SIGMA P.E. (pCi/L) (75999)	Thorium -232, SSMDC (pCi/L)	Gross alpha, residue procedure, as TH-230 (pCi/L) (04126)	Gross alpha, 2 SIGMA P.E. (pCi/L) (75987)	Gross beta, residue procedure, as CS-137 (pCi/L) (03515)	Beta, 2 SIGMA P.E. (pCi/L) (75989)	Turbidity, field (NTU) (61028)	Sediment, suspended (mg/L) (80154)
291203	R3 (NA)	2/23/2000	1143	1323	--	--	--	--	<3	1.68	<4	3.63	1.32	--
291371	R1 (NA)	12/8/1999	1124	1128	--	--	--	--	--	--	--	--	5.01	1.5
291371	R1 (NA)	12/8/1999	1137	1140	--	--	--	--	--	--	--	--	5.46	--
291371	R2 (NA)	12/8/1999	1323	1341	--	--	--	--	--	--	--	--	5.83	1.5
291371	R3 (NA)	12/8/1999	1507	1521	--	--	--	--	--	--	--	--	2.13	--
291371	0.45F (ULTRAFILTER, RETENTATE)	12/8/1999	1640	1712	--	--	--	--	--	--	--	--	1.06	--
291371	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/8/1999	1640	1720	--	--	--	--	--	--	--	--	1.06	--
291371	0.45F (ULTRAFILTER, RETENTATE)	12/8/1999	1720	--	--	--	--	--	--	--	--	--	.93	--
291371	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/8/1999	1721	--	--	--	--	--	--	--	--	--	.93	--
291379	R2 (NA)	1/6/2000	1011	1019	--	--	--	--	--	--	--	--	3.48	--
291379	R2 (NA)	1/6/2000	1011	1019	--	--	--	--	--	--	--	--	--	--
291379	0.45F (ULTRAFILTER, RETENTATE)	1/6/2000	1155	1301	--	--	--	--	--	--	--	--	--	--
291379	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	1/6/2000	1155	1307	--	--	--	--	--	--	--	--	--	--
291372	R2 (NA)	2/1/2000	1015	1022	--	--	--	--	--	--	--	--	.73	--
291372	R2 (NA)	2/1/2000	1015	1022	--	--	--	--	--	--	--	--	--	--
291372	R3 (NA)	2/1/2000	1046	1108	--	--	--	--	--	--	--	--	--	--

**Table 7B.** Concentrations of radionuclides in filtered and unfiltered concurrent laboratory duplicate and sequential replicate samples of water from observation wells and equipment blank, at or near the BOMARC Missile Facility, Ocean County, New Jersey, 1999–2000.—Continued

[Data are sorted by well depth; pCi/L, picocurie per liter; P.E., precision estimate; SSMDC, sample-specific minimum detectable concentration; <, less than; K, thousand; NA, not applicable; --, no data; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS) in which individual samples are identified by sample number.]

U.S. Geological Survey well number	Sample designation (and filter type) <sup>1</sup>	Date (month/day/year)	Begin sample collection, time	End sample collection, time	Thorium -230, SSMDC (pCi/L)	Thorium -232 (pCi/L) (75976)	Thorium -232, 2 SIGMA P.E. (pCi/L) (75999)	Thorium -232, SSMDC (pCi/L)	Gross alpha, residue procedure, as TH-230 (pCi/L) (04126)	Gross alpha, 2 SIGMA P.E. (pCi/L) (75987)	Gross beta, residue procedure, as CS-137 (pCi/L) (03515)	Beta, 2 SIGMA P.E. (pCi/L) (75989)	Turbidity, field (NTU) (61028)	Sediment, suspended (mg/L) (80154)
291375	0.45F (ULTRAFILTER, RETENTATE)	12/3/1999	1454	1507	--	--	--	--	--	--	--	--	--	--
291375	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	12/3/1999	1524	1613	--	--	--	--	--	--	--	--	--	--
291374	R2 (NA)	12/15/1999	1008	1055	--	--	--	--	--	--	--	--	0.69	--
291376	R2 (NA)	2/15/2000	1016	1036	--	--	--	--	--	--	--	--	1.37	--
291376	R2	2/15/2000	1016	1036	--	--	--	--	--	--	--	--	--	--
291376	R3 (NA)	2/15/2000	1120	1208	--	--	--	--	<3	2.37	<4	3.99	.67	--
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1315	1518	--	--	--	--	<3	1.95	<4	3.84	.54	--
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1315	1518	--	--	--	--	--	--	--	--	--	--
291376	0.45F (ULTRAFILTER, RETENTATE)	2/15/2000	1537	1626	--	--	--	--	--	--	--	--	.55	--
291376	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/2000	1538	1642	--	--	--	--	--	--	--	--	.55	--
291376	0.0029F (ULTRAFILTER, 10K DALTON PERMEATE)	2/15/2000	1538	1642	--	--	--	--	--	--	--	--	--	--
291378	R1 (NA)	8/25/1999	1143	1151	--	--	--	--	--	--	--	--	38.9	--

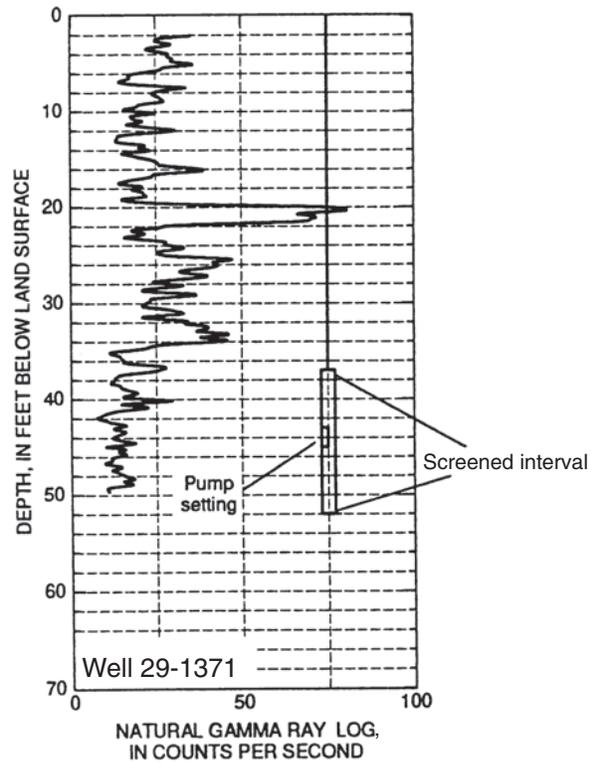
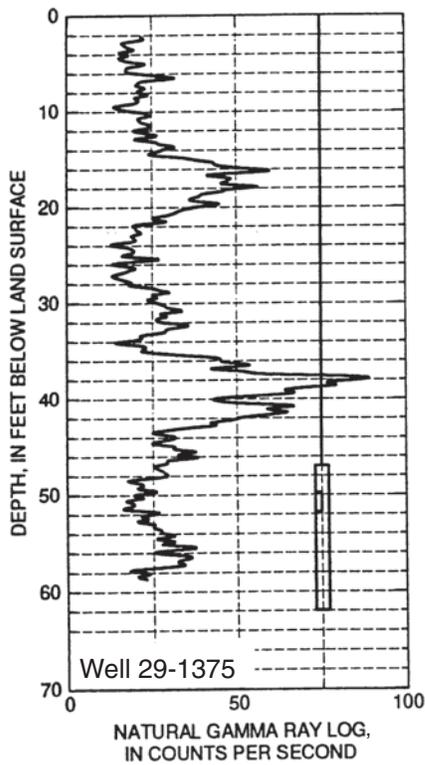
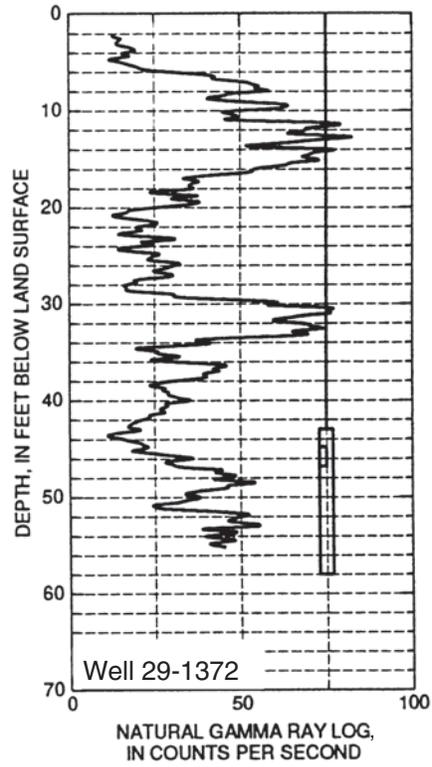
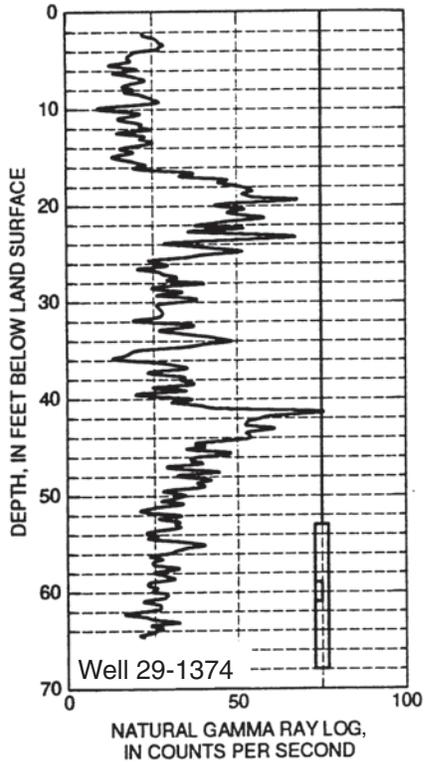
<sup>1</sup> Sample designation type: R1, unfiltered, initial; R2, unfiltered, turbidity generally less than 10 NTU and slowly decreasing; RTi, unfiltered, turbidity not stable and variable; R3, unfiltered, turbidity stable and generally less than 5 NTU; 0.45Fa, filtered, 45-micron filter; 0.45F, filtered with 45-micron capsule filter and from retentate port from 0.0029-micron ultrafilter, F0.0029, filtered sequentially through 0.45-micron capsule filter and 0.0029-micron ultrafilter; F0.05, filtered sequentially through 0.45-micron and 0.05-micron capsule filters.

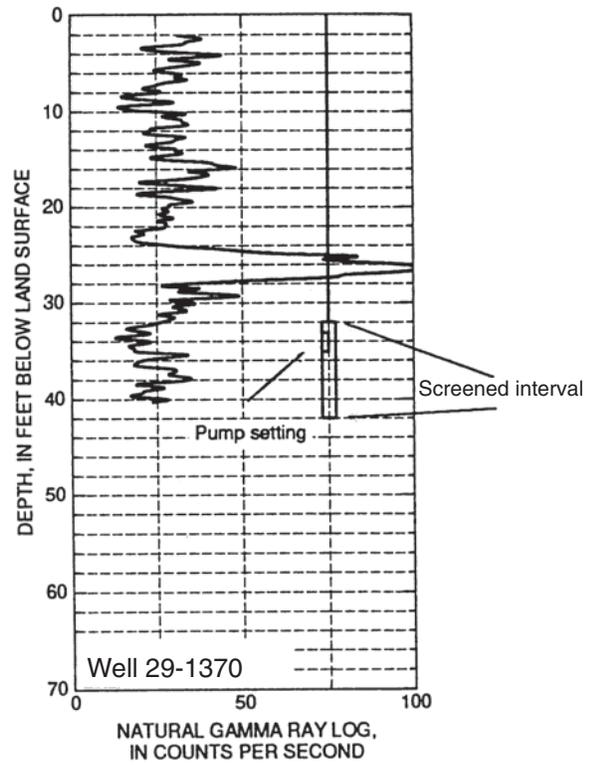
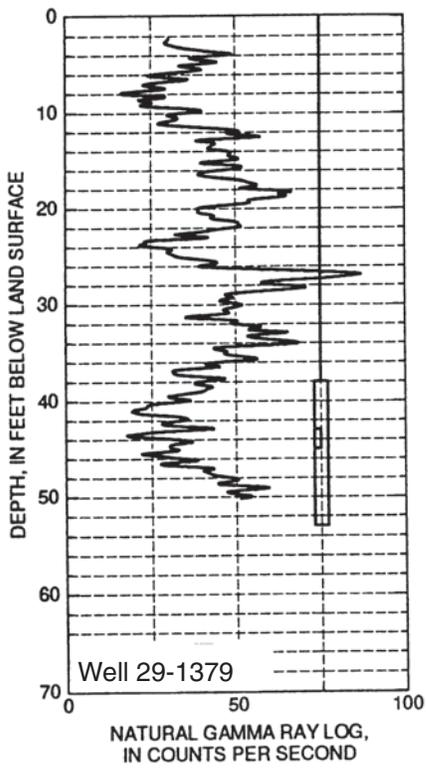
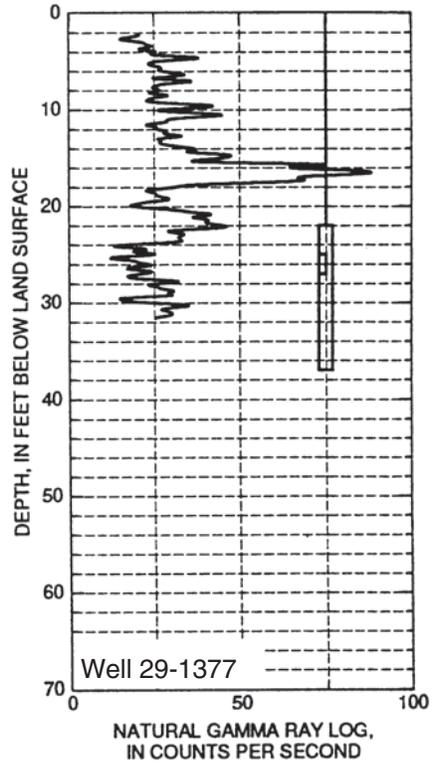
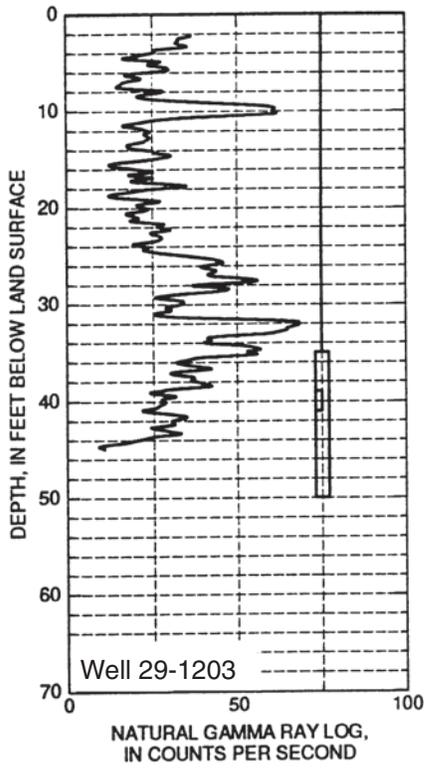
<sup>2</sup> Sample medium: S, replicate; Q, equipment blank.

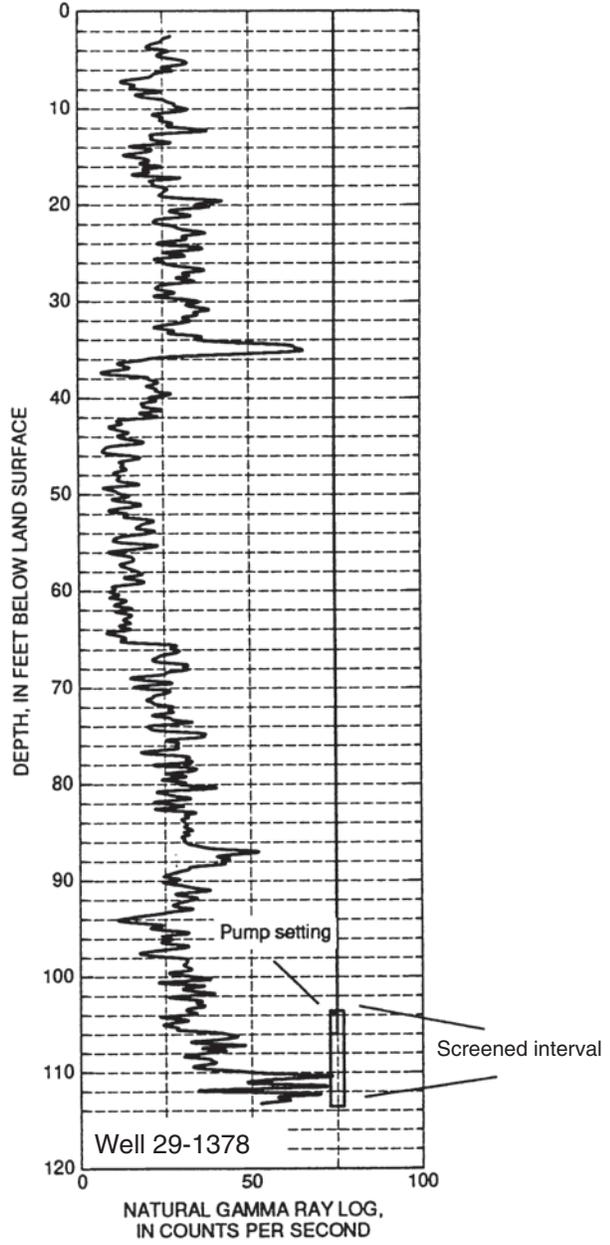
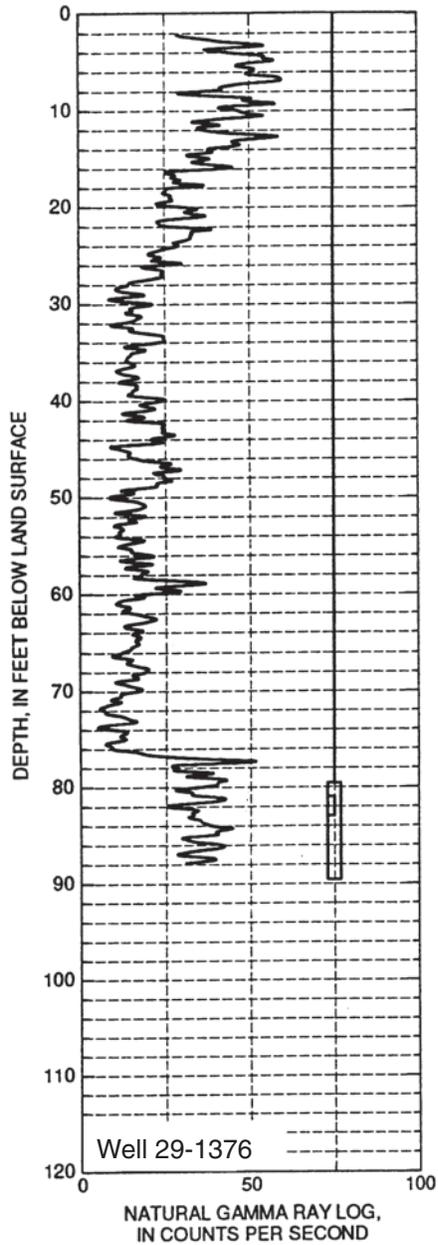
<sup>3</sup> Replicate: 10, concurrent; 20, sequential.

**Appendix 1. Natural Gamma Ray Logs,  
Screened Interval, and Pump Setting for Wells at  
the BOMARC Missile Facility, Ocean County, N.J.**

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Appendix 1c.

For additional information, write to:

Director  
U.S. Geological Survey  
New Jersey Water Science Center  
Mountain View Office Park  
810 Bear Tavern Rd., Suite 206  
West Trenton, NJ 08628

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<http://nj.usgs.gov/>