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OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

DUAL WALL REVERSE CIRCULATION DRILLING WITH MULTI-LEVEL GROUNDWATER SAMPLING FOR GROUNDWATER CONTAMINANT PLUME DELINEATION AT PADUCAH GASEOUS DIFFUSION PLANT, PADUCAH, KENTUCKY

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MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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Eric. E. Morti[1]
John L. Zutman[2]
Douglas A. Pickering[2]

[1] Martin Marietta Energy Systems, Inc., Paducah Environmental Restoration Department
[2] Health Sciences Research Division

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ACRONYMS, ABBREVIATIONS, AND INITIALISMS

CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
1,2-DCE	1,2-dichloroethene
DOE	U.S. Department of Energy
DWRC	dual wall reverse circulation
ER	Environmental Restoration
FSP	field sampling plan
ft	feet
gal	gallon
GC	gas chromatograph
GJ	Grand Junction
h	hours
IDW	investigative derived wastes
in.	inches
μL	microliter
μm	micron
min	minutes
NEPA	National Environmental Policy Act
ORNL	Oak Ridge National Laboratory
PGDP	Paducah Gaseous Diffusion Plant
ppb	parts per billion
RGA	regional gravel aquifer
s	second
TCE	trichloroethene
UCRS	upper continental recharge system
VOC	volatile organic compound
vs	versus

ABSTRACT

Dual wall reverse circulation (DWRC) drilling was used to drill 48 borings during a groundwater contaminant investigation at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky. This method was selected as an alternative to conventional hollow stem auger drilling for a number of reasons, including the expectation of minimizing waste, increasing the drilling rate, and reducing the potential for cross contamination of aquifers. Groundwater samples were collected from several water-bearing zones during drilling of each borehole. The samples were analyzed for volatile organic compounds using a field gas chromatograph. This approach allowed the investigation to be directed using near-real-time data. Use of downhole geophysical logging, in conjunction with lithologic descriptions of borehole cuttings, resulted in excellent correlation of the geology in the vicinity of the contaminant plume. The total volume of cuttings generated using the DWRC drilling method was less than half of what would have been produced by hollow stem augering; however, the cuttings were recovered in slurry form and had to be dewatered prior to disposal. The drilling rate was very rapid, often approaching 10 ft/min; however, frequent breaks to perform groundwater sampling resulted in an average drilling rate of < 1 ft/min. The time required for groundwater sampling could be shortened by changing the sampling methodology. Analytical results indicated that the drilling method successfully isolated the various water bearing zones and no cross contamination resulted from the investigation.

1. INTRODUCTION

This paper describes the drilling and sampling methods used to delineate a groundwater contaminant plume at the Paducah Gaseous Diffusion Plant (PGDP), Paducah, Kentucky. The project (referred to as Groundwater Monitoring Phase IV) was unique in that it relied upon dual wall reverse circulation (DWRC) drilling, representing an advance in site-characterization methodology for the plant. The DWRC drilling method was used to drill 48 borings averaging about 150 ft deep and one boring 350 ft deep. The method was selected based on the following reported characteristics:

- provides a fast and efficient method for drilling exploratory borings while allowing continuous monitoring of formation samples;
- significantly reduces the possibility of cross contamination within the borehole because there is no annular space between the drill string and the borehole wall;
- allows discrete water samples to be collected from within the inner tube of the drill string;
- produces cutting volumes near theoretical hole size and simplifies handling because the cuttings are deposited directly into drums;
- allows geophysical logging to be conducted inside the inner drill tube; and
- allows pressure grouting of the boring as the drill string is withdrawn, thus preventing later cross contamination between water-bearing zones.

This report evaluates the strengths and weaknesses of using this method for delineating groundwater contaminant plumes in similar hydrogeologic settings.

1.1 BACKGROUND

PGDP, a U.S. Department of Energy (DOE) facility located in western Kentucky, enriches uranium for commercial nuclear reactors using the gaseous diffusion process.

Past industrial and construction activities at PGDP have resulted in contamination of groundwater in the shallowest aquifer, the regional gravel aquifer (RGA). The northeast plume was identified during a two-phased Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) site investigation conducted from 1989 to 1991. Groundwater Monitoring Phase IV was performed in 1994 to further determine the horizontal and vertical extent of the northeast plume. Groundwater in the northeast plume is contaminated with trichloroethene (TCE) and ^{99}Tc. The plume appears to emanate from the eastern half of the plant and extends approximately 2.5 miles northeast, with an estimated areal extent of 1.2 miles^2. Prior to Groundwater Monitoring Phase IV, 17 wells in 11 clusters had penetrated the plume, mainly around the edges (Fig. 1).

1.2 PURPOSE

In spite of previous investigations, no definitive source(s) of contamination had been determined for the northeast plume, nor had the boundaries of the plume been determined, either horizontally or vertically. Investigators suspected that the northeast plume was formed by the coalescence of several smaller plumes emanating from different sources. It was postulated that these individual plumes had "hot spots" and were possibly separated from one another by areas of clean, uncontaminated groundwater. In addition, the presence or absence of contamination in the deeper aquifer system, the McNairy Formation, had not been determined. Thus, the objectives of the investigation were to:

1. identify possible sources of contamination for the northeast plume,
2. describe the hydrologic interaction of the upper McNairy Formation with the overlying RGA,
3. characterize the vertical and horizontal extent of contamination,
4. locate contaminant hot spots.

These objectives were used to develop a field sampling plan (FSP), which described the Groundwater Phase IV investigation.

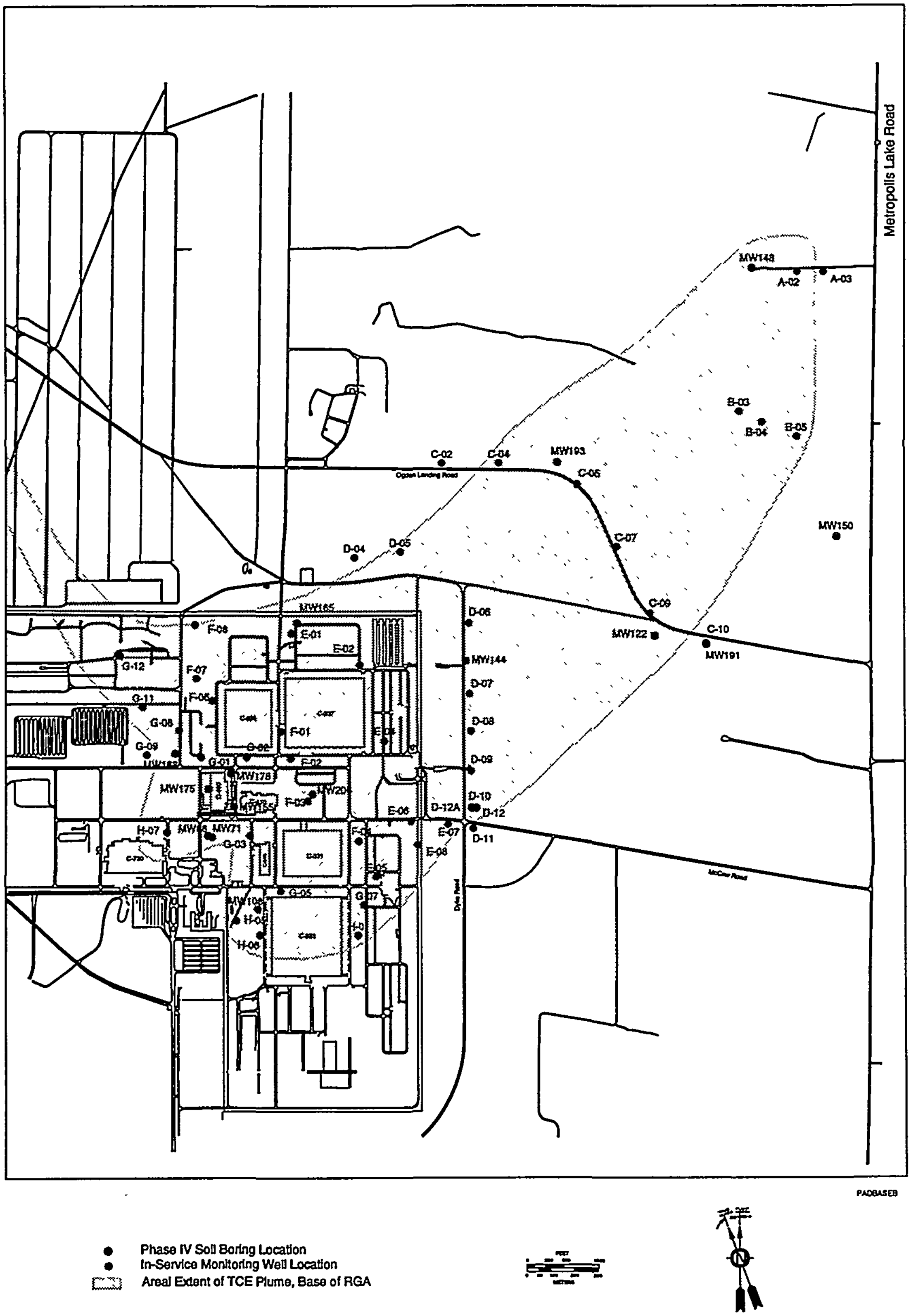

Fig. 1. Map of Groundwater Monitoring Phase IV drilling locations.

The FSP proposed a series of sampling transects, three transects within the plant and four outside the plant, that would provide cross sections of the plume along seven lines. These are shown on Fig. 1 as NEPA corridors and the E, F, and G transects. The off-site transects were planned along roads, where possible, to improve accessibility and reduce the physical impact of the investigation. The transects were spaced roughly 1500 ft apart, with individual borings approximately 500 ft apart within each transect. Except for transect B, each transect included an existing monitoring well to serve as a reference point for sample depth selection. The FSP provided further description of the location and purpose of individual transects. Table 1 lists the borings drilled, samples collected, and supplementary data collected during the investigation.

2. GEOLOGY

The subsurface at PGDP consists of Cretaceous, Tertiary, and Quaternary sediments unconformably overlying Paleozoic (Mississippian) bedrock (Clausen et al. 1992). Figure 2 shows a generalized stratigraphic column of the geology in the Paducah area.

Immediately overlying Mississippian bedrock at PGDP is the Upper Cretaceous McNairy Formation, not exposed near PGDP. Data reported by ERCE (1990) indicate sand may account for 40 to 50% of the McNairy Formation near PGDP. The Paleocene Porters Creek clay occurs in southern portions of the site, increasing in thickness southward. This unit is occasionally exposed in stream beds south of PGDP. The Porters Creek clay subcrops along a buried terrace slope that extends east-west across the site (Fig. 3). Eocene sediments overlie the Porters Creek clay in the extreme southern portion of the DOE reservation. The Eocene sediments near the site have not been differentiated into specific formational units.

Table 1. Description of Groundwater Monitoring Phase IV investigation

Borehole ID	Start date	End date	Total depth, ft	Number of water samples	Geophysical logs	Solid waste; liquid waste	Comments
A2	07/26/94	07/27/94	155	5	Gamma Neutron	5 drums 350 gal	Attempted to sample at 38 ft but insufficient water.
A3	08/04/94	08/05/94	155	4	Gamma Neutron	NR NR	Unable to sample at 115 and 120 ft due to heaving sand.
B3	08/06/94	08/10/94	150	6	Gamma Neutron	NR NR	Performed duel sampling with packer and with micropurge.
B4	08/10/94	08/16/94	150	5	Gamma Neutron	6 drums 250 gal	Drill rods left in hole during work break.
B5	08/17/94	08/19/94	150	5	Gamma Neutron	4 drums 250 gal	No overshot casing used.
C2	08/24/94	08/25/94	150	3	Gamma Neutron	4 drums 250 gal	No McNairy water samples
C4	07/15/94	07/22/94	151	5	Gamma Neutron	5 drums 800 gal	Had to trip hole for lost pump parts.
C5	07/09/94	07/12/94	150	4	Gamma Neutron	7 drums 500 gal	No McNairy water samples collected.
C7	07/14/94	07/16/94	150	6	Gamma Neutron	4 drums 500 gal	No overshot casing used.
C9	07/12/94	07/13/94	150	4	Gamma Neutron	4 drums 700 gal	No overshot casing used.
C10	08/19/94	08/22/94	150	5	Gamma Neutron	5 drums 400 gal	No overshot casing used.
D4	07/09/94	07/12/94	150	5	Gamma Neutron	6 drums 500 gal	No overshot casing used.
D5	07/28/94	08/02/94	150	5	Gamma Neutron	11 drums 500 gal	Drill rods were left in hole during work break.
D6	06/23/94	06/27/94	147	6	Gamma Neutron Density	5 drums NR	Overshot casing used.
D7	06/22/94	06/25/94	150	7	Gamma Neutron Density	22 drums NR	Overshot casing used.
D8	06/27/94	06/30/94	150	7	Gamma Neutron Density	10 drums 300 gal	Overshot casing used.
D9	06/28/94	06/30/94	150	5	Gamma	5 drums NR	No overshot casing used.

Table 1. (continued)

Borehole ID	Start date	End date	Total depth, ft	Number of water samples	Geophysical logs	Solid waste; liquid waste	Comments
D10	07/07/94	07/09/94	150	6	Gamma Neutron Density	NR NR	No overshot casing used.
D11	07/07/94	07/08/94	150	4	Gamma	6 drums 600 gal	No overshot casing used.
D12	07/12/94	07/15/94	150	5	Gamma	NR NR	Overshot casing to 110 ft, gamma log both with and without overshot.
D12A	07/22/94	07/25/94	150	7	Gamma Neutron	NR NR	Overshot casing to 110 ft.
E1	10/22/94	10/24/94	140	6	Gamma Neutron	6 drums 200 gal	No overshot casing used.
E2	08/04/94	08/06/94	150	6	Gamma	7 drums 500 gal	No overshot casing used.
E4	07/28/94	08/02/94	117	3	Gamma	NR NR	No overshot casing used; pipe stuck in hole over work break.
E6	07/23/94	07/27/94	151	6	Gamma Neutron	7 drums 250 gal	No overshot casing used; bailed four out of six samples.
E7	09/07/94	09/09/94	150	6	Gamma Neutron	5 drums 400 gal	No overshot casing used; bailed three out of six samples.
E8	10/13/94	10/18/94	155	4	Gamma Neutron	6 drums 400 gal	No overshot casing used.
F1	10/18/94	10/20/94	165	5	Gamma Neutron	16 drums 800 gal	No overshot casing used; abundant heaving sand in McNairy.
F2	10/10/94	10/12/94	170	5	Gamma Neutron	5 drums 350 gal	No overshot casing used.
F3	09/20/94	09/22/94	150	5	Gamma Neutron	6 drums 300 gal	No overshot casing used; bailed two out of five samples.
F4	10/20/94	10/21/94	165	4	Gamma Neutron	6 drums 200 gal	No overshot casing used.
F5	10/07/94	10/08/94	150	5	Gamma Neutron	NR NR	No overshot casing used.
F6	09/07/94	09/09/94	150	6	Gamma Neutron	5 drums NA	No overshot casing used; bailed two out of six samples.
F7	09/14/94	09/15/94	150	6	Gamma Neutron	5 drums 800 gal	No overshot casing used; bailed three out of six samples.

Table 1. (continued)

Borehole ID	Start date	End date	Total depth, ft	Number of water samples	Geophysical logs	Solid waste; liquid waste	Comments
F8	09/27/94	09/29/94	350	9	Gamma Neutron	48 drums 1000 gal	No overshot casing used.
G1	08/22/94	08/23/84	155	6	Gamma Neutron	4 drums 500 gal	No overshot casing used.
G2	08/10/94	08/17/94	160	7	Gamma Neutron	11 drums 500 gal	No overshot casing used; bailed four out of seven samples.
G3	08/18/94	08/20/84	150	5	Gamma	4 drums NR	No overshot casing used.
G5	08/24/94	08/25/94	150	4	Gamma Neutron	5 drums 500 gal	No overshot casing used; bailed one sample.
G7	08/14/94	08/15/94	150	4	Gamma Neutron	5 drums 250 gal	No overshot casing used; bailed two out of four samples.
G8	09/09/94	09/10/94	150	5	Gamma Neutron	5 drums 700 gal	No overshot casing used; bailed one sample.
G9	09/12/94	09/14/94	150	5	Gamma Neutron	5 drums 800 gal	No overshot casing used; bailed two samples.
G11	09/15/94	09/21/94	150	6	Gamma Neutron	5 drums 250 gal	No overshot casing used; bailed one sample. Rods left in boring during work break.
G12	10/05/94	10/07/94	150	6	Gamma Neutron	NR NR	No overshot casing used.
H1	09/09/94	09/10/94	100	2	Gamma	5 drums 300 gal	No overshot casing used; bailed two samples.
H5	09/24/94	09/27/94	150	6	Gamma Neutron	7 drums 350 gal	No overshot casing used.
H6	09/12/94	09/13/94	100	3	Gamma Neutron	4 drums 250 gal	No overshot casing used. No RGA.
H7	09/22/94	09/24/94	150	6	Gamma Neutron	5 drums 300 gal	No overshot casing used.

NR = not recorded

System	Series	Formation	Lithology	Thickness, ft	Description
QUATERNARY	Pleistocene and Recent	Alluvium		0-40	Brown or gray sand and silty clay or clayey silt with streaks of sand.
QUATERNARY	Pleistocene	Loess		0-43	Brown or yellowish-brown to tan to gray unstratified silty clay.
QUATERNARY	Pleistocene	Continental Deposits		3-121	Clay facies: orange to yellowish-brown to brown clayey silt, some very fine sand, trace of fine sand to gravel, often micaceous.
TERTIARY	Pliocene Miocene?				Gravel facies: reddish-brown silty and sandy chert gravel and beds of gray sandy gravel, silt, and clay.
TERTIARY	Eocene	Jackson, Claiborne, and Wilcox Formations		0-200+	Red, brown, or white fine- to coarse-grained sand. Beds of white to dark gray clay are distributed at random.
				0-100+	White to gray sandy clay, clay conglomerate and boulders, scattered clay lenses, and lenses of coarse red sand. Black to dark gray lignitic clay, silt, or fine-grained sand.
TERTIARY	Paleocene	Porters Creek Clay		0-200	Dark gray, slightly to very micaceous clay. Fine-grained clayey sand, commonly glauconitic in the upper part. Glauconitic sand and clay at the base.
		Clayton Formation		?	Lithologically similiar to uderlying McNairy formation.
CRETACEOUS		McNairy Formation		200-300	Grayish-white to dark gray micaceous clay, often silty, interbedded with light gray to yellowish-brown very fine to medium-grained sand. The upper part is mostly clay; the lower part is predominantly micaceous fine sand.
		Tuscaloosa Formation		?	White, well-rounded or broken chert gravel with clay.
MISSISSIPPIAN		Mississippian Carbonates		500+	Dark gray limestone and interbedded chert, some shale.

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Fig. 2. Generalized stratigraphic column.

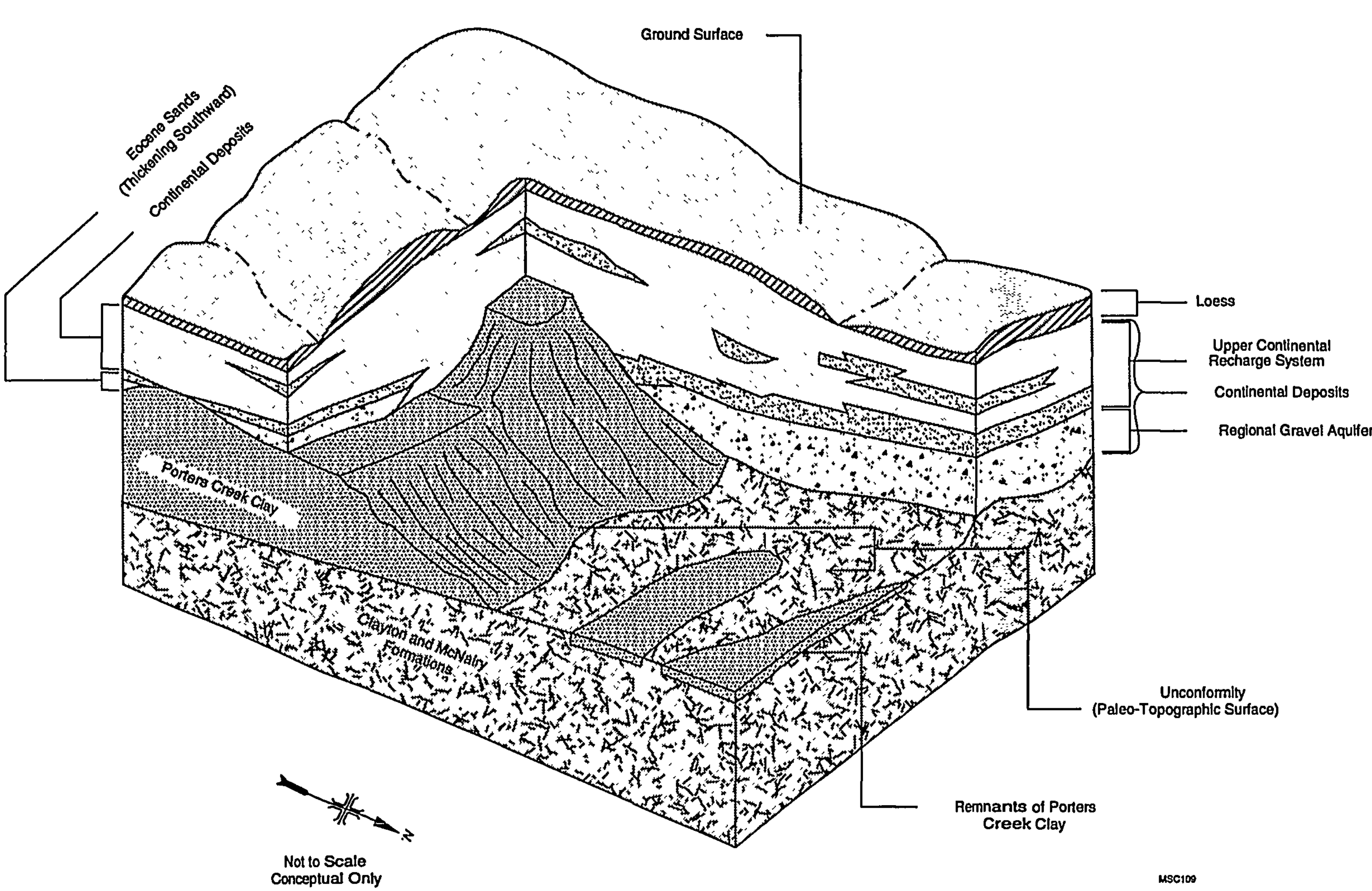

Fig. 3. Schematic block diagram of stratigraphy near PGDP.

The base of the Miocene(?), Pliocene, and Pleistocene continental deposits represents a nonconformity. The thicker sequence of Pleistocene continental deposits represents a valley fill. As shown in Fig. 3, a schematic block diagram illustrating conceptual site stratigraphic relationships, the unconformable base of the continental deposits exhibits steps or terraces. Previous investigators at the site subdivided the continental deposits into a lower unit (gravel facies) and an upper unit (clay facies). Thicker deposits of lower gravel facies, up to 50 ft in thickness, exist in deeper scour channels of the ancestral Tennessee River and form the RGA. The thicker deposits trend east-west across the site and pinch out against the terrace slope under the southern end of PGDP.

The upper continental deposits are interpreted as predominantly lacustrine deposits. Sand- and gravel-dominated lithofacies exist at different elevations throughout the upper continental deposits. However, most sand and gravel deposits occur at consistent elevations. The base of the coarser clastics represents local erosional nonconformities, useful for delineation of depositional events. Lenticular sand bodies represent scour and fill deposition, while other coarse clastics occur in blanket deposits.

Loess overlies the continental deposits throughout the site and is difficult to distinguish from the underlying lacustrine sediments. The Groundwater Investigation Phase III project report provides more detail regarding the site geology (Clausen et al. 1992).

3. SITE HYDROGEOLOGY

The local groundwater flow system exists within sediments described in Sect. 2 as sands of Cretaceous McNairy Formation and Eocene Wilcox Formation, Pliocene and Pleistocene lower continental deposits, Pleistocene upper continental deposits, and Holocene alluvium.

The major elements of the flow system are defined as follows:

1. McNairy flow system: this term refers to the McNairy Formation, which consists of interbedded and interlensing sand, silt, and clay. Sand facies account for as much as 40 to 50% of the total formation thickness of approximately 225 ft.

2. Terrace gravels: these gravel deposits, found at elevations higher than 350 ft above median sea level and believed related to Pliocene alluvial fan deposition, usually lack sufficient thickness and saturation to form an aquifer.

3. RGA: the Plio-Pleistocene sand and gravel facies of the lower continental deposits of sufficient thickness and saturation to form an aquifer. These gravels, described in Sect. 2, are commonly thicker than the Pliocene gravel deposits. Measured thicknesses average 30 ft and range up to 50 ft along an axis that trends east-west through the site. The RGA is the primary aquifer utilized locally. Additionally, this term includes the Holocene alluvium found adjacent to the Ohio River.

4. Upper continental recharge system (UCRS): the sand- and gravel-dominated lithofacies found at different elevations throughout the predominantly clayey silt of the upper continental deposits. The sand and gravel lithofacies appear relatively discontinuous in cross section but may be more connected in three dimensions.

Recharge to the south and discharge to the north of PGDP bound the local groundwater flow system. One area of recharge has resulted in a groundwater divide southwest of PGDP. North of the divide, groundwater flows toward the Ohio River, which is local base level for the system.

Surface water in the recharge area may take one of several paths to the system base level. The path of interest for contaminant migration has several steps. In the recharge area, surface water enters the continental deposits and Eocene sands. As the water moves north, it moves from the local Eocene sands into the terrace gravels. Water continues to move north, either discharging into local streams or into the RGA. The RGA receives some water flowing laterally from the terrace gravels and is also recharged by downward flow from the surface through the UCRS. This is the predominant groundwater and contaminant pathway at PGDP. The RGA serves as a major groundwater pathway, with eventual discharge to the river.

The hydraulic relationship between the RGA and the underlying McNairy flow system is not completely understood. In locations where the Porters Creek clay separates the aquifers, there may be little hydraulic interaction, although differences in hydraulic head imply flow between the two units and similar responses to seasonal conditions indicate a complex relationship. Section 6 of the Groundwater Investigation Phase III report provides more detail of the hydrogeology at PGDP (Clausen et al. 1992).

4. FIELD ACTIVITIES

4.1 SCOPE

Field activities completed for this project included drilling soil borings, collecting soil cuttings for lithologic description and archival, collecting groundwater samples for field screening and laboratory analysis, collecting borehole geophysical data, abandoning boreholes, dewatering drill cuttings, and managing investigative derived wastes (IDW).

A statement of work was prepared to procure a subcontractor to drill the required soil borings and collect the soil samples. The drilling subcontractor was also responsible for geophysical logging of the borings and providing a waste separation system for dewatering drill cuttings. PGDP Environmental Restoration (ER) personnel collected the groundwater samples, and Oak Ridge National Laboratory/Grand Junction office (ORNL/GJ) personnel supervised the drilling and sampling, prepared lithologic logs, performed health and safety monitoring, operated the field analytical laboratory, and managed IDW.

4.2 DRILLING METHOD

The DWRC drilling system consisted of two concentric strings of pipe (Fig. 4). Top-head drive rotary power and a tricone bit were used to advance the drill string. An air compressor and diaphragm pump provided the drilling fluid as either air or air/water mist. The driller regulated the air/water mix depending on the water content of the interval being drilled; for instance, if the interval contained free water, then only air was injected. Air/water mist was forced down the annulus between the two pipe walls and exited around the outside of the bit into the borehole. The mist assisted with cutting the formation and returned through the center of the bit carrying the cuttings to the surface. The drilling rate averaged about 1.5 ft/min, and the cuttings return rate was about 60 ft/s. Thus, there was very little travel time for cuttings to reach the surface, and the geologist was able to detect lithologic breaks almost as soon as the bit encountered them. The drilling fluid contacted the borehole wall only at the bit, and since the bit outer diameter was slightly larger than the drill pipe (4⅝ in. vs 4¼ in.), the cuttings closed around the pipe, significantly reducing the potential for vertical cross contamination. At the surface, the cuttings were routed from the top head to a cyclone separator and discharged into 55-gal drums. The drums were situated in a mud tank to catch any overflow. Once filled, the drums were labelled and transported to a staging area at the decontamination facility. Excess water in the mud tanks was pumped into a truck-mounted poly-tank and transported to the staging area.

The following general procedure was followed in drilling and sampling the boreholes:

1. The borehole was advanced as described above to the first water sampling point, generally a sandy zone in the UCRS or the top of the RGA. Drill cuttings were collected continuously, and samples were consolidated into 5-ft intervals for description and archival. The geologist prepared a borehole summary with a detailed lithologic description. Work progress was recorded in a field logbook. At the beginning of the investigation, overshot casing was advanced to within a few feet of the bit prior to water sampling as an additional means of isolating the interval to be sampled. The use of the overshot casing increased the drilling time by 4 to 6 h per borehole and almost doubled the amount of drilling spoils, requiring the drill string to be removed and reinserted in the boring (tripped) and the boring to be cleared of excess water and cuttings each time a trip was made. Use of this casing was discontinued after a field experiment showed that there were essentially no differences in contaminant

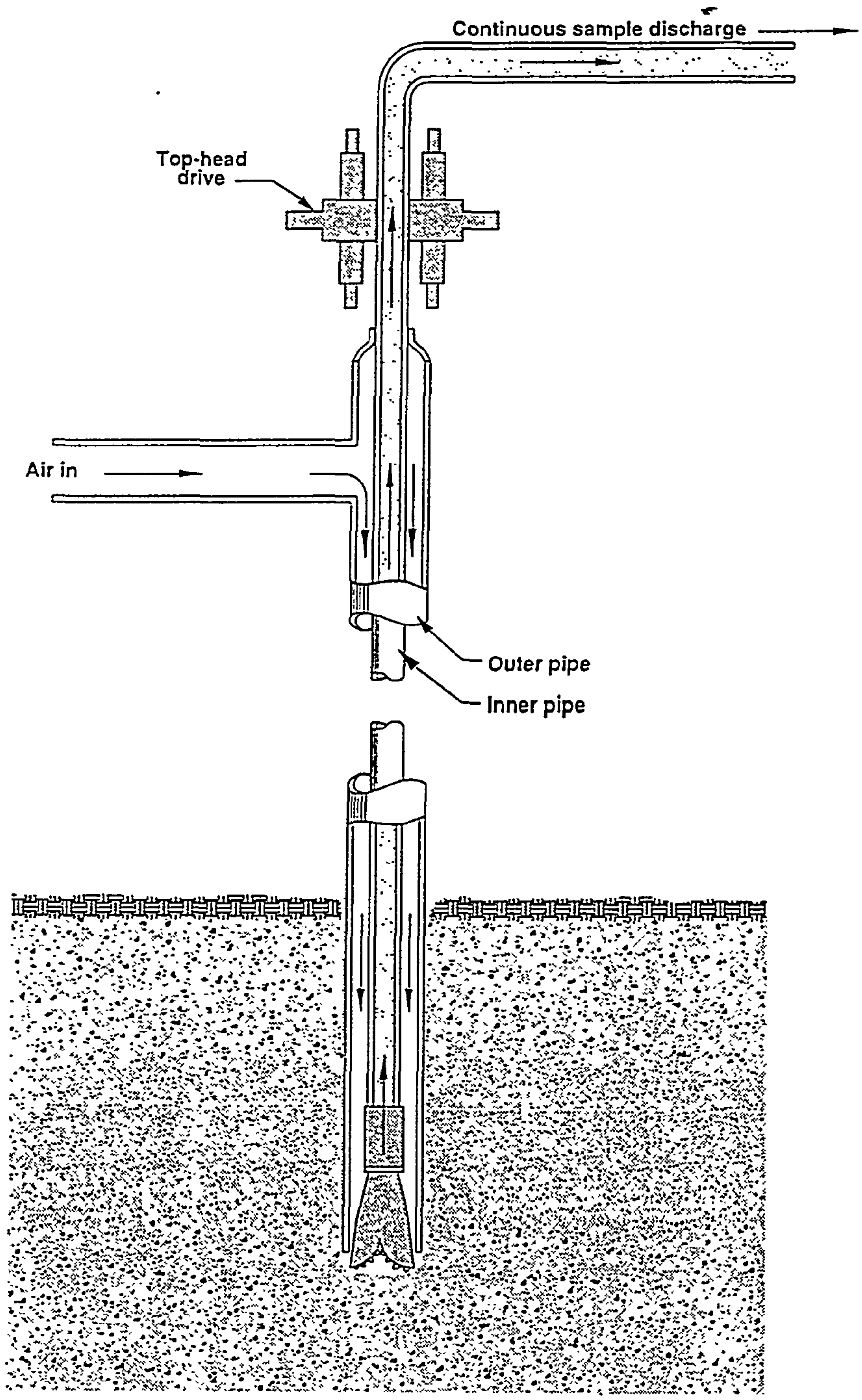

Fig. 4. DWRC drilling system.

concentrations in water samples collected with or without the use of the overshot casing and that geophysical logs run inside the dual tube were very similar to those run with only the overshot casing in place.

2. Once the interval to be sampled was reached, excess water and cuttings were flushed from the system and a bladder pump and packer assembly were lowered down into the inner drill tube (Fig. 5). The packer was inflated to seal off the interval to be sampled, which was then purged with the bladder pump. Water quality parameters were monitored continuously during purging. The interval was considered purged when temperature, pH, and conductivity had stabilized for three consecutive readings. Mid-way through the project, micropurging was adopted, which reduced sampling time and purge-water volumes. The requisite water samples were collected in appropriate containers and placed in a cooler on ice for transport to the laboratory. All samples were labelled and recorded in accordance with PGDP field operating procedures. Some intervals were sampled with a bailer instead of the pump-packer assembly if there was insufficient water for pumping or if flowing sand was a problem.

   Water sampling proved to be the most problematic portion of the investigation. The bladder pump and packer assembly often jammed in the drill rods due to heaving sand. Moreover, the bladder pumps required frequent replacement of Teflon™ bladders, and the packers would not inflate and seal properly. Once micropurging was adopted, the packers were no longer needed.

3. After sampling was completed for an interval, sampling equipment was removed for decontamination, and drilling resumed until the next interval to be sampled was reached. Water samples were generally collected in the following zones: the UCRS; the top, middle, and bottom of the RGA; and the top of the McNairy Formation. Additional samples were often collected from other sandy intervals encountered in the McNairy Formation. Thus, the stop-and-go drilling and sampling were repeated

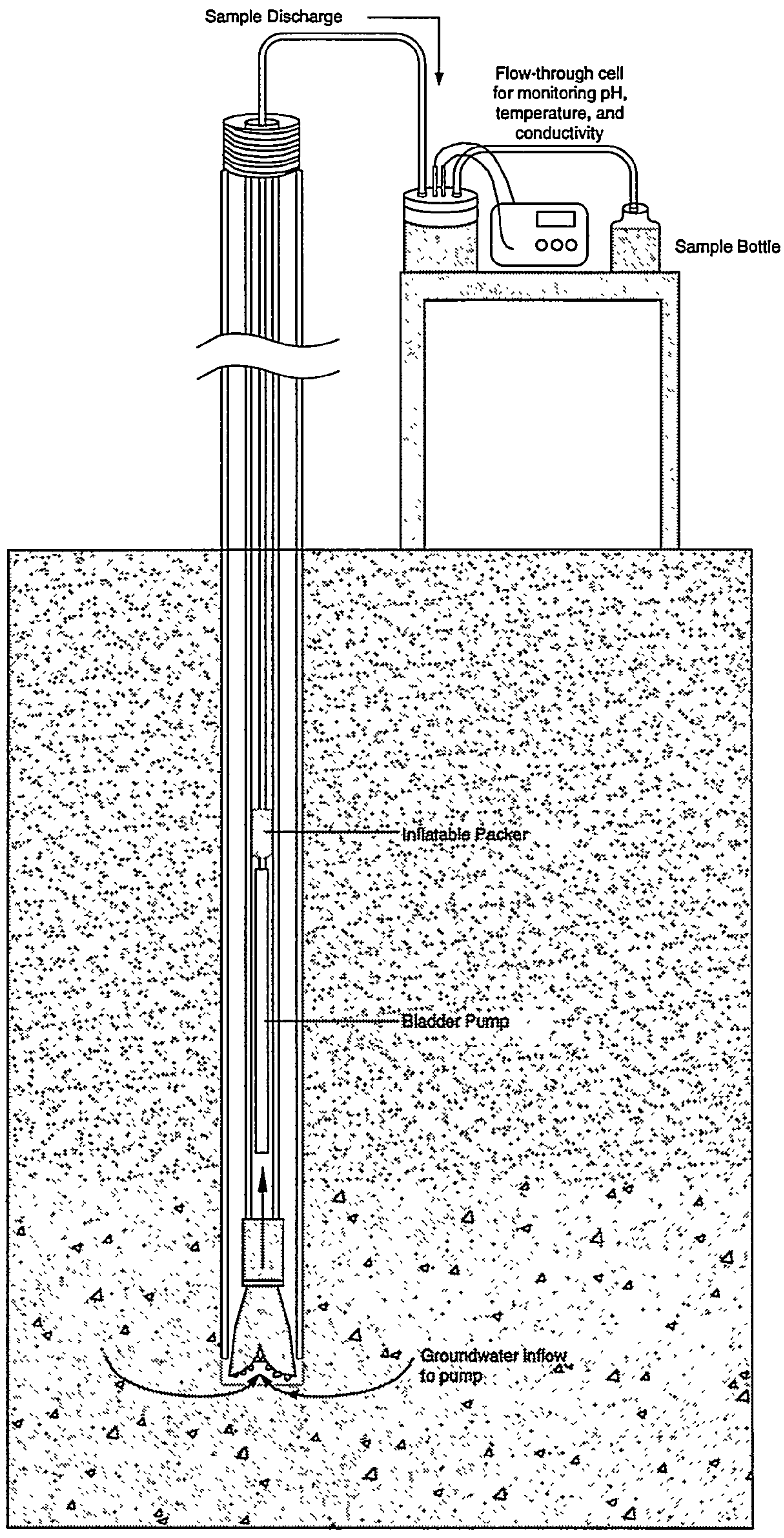

Fig. 5. Groundwater sampling through dual tube system.

as many as eight times per boring. Water sampling was generally completed for each interval in 1 to 2 h. Thus, it often took more than 12 h to complete all of the water sampling for a single boring. The drilling crew and rig were on standby during the sampling.

4. After reaching the total depth to be drilled, all boreholes were logged for natural gamma radiation, and most were also logged with a neutron tool. A few boreholes were logged with a density tool; however, this log was eliminated early in the project because the signal attenuation caused by the drill rods masked the information response. The combination of gamma radiation and neutron logging provided excellent data and aided in correlating the borehole lithologic logs across the area.

5. All boreholes were abandoned using a high-solids bentonite grout. The grout was mixed at the surface and pumped down the center of the drill string as the drill pipe was withdrawn, thus sealing off all water-bearing zones and preventing cross contamination of aquifers. The drill rig was then moved to the decontamination facility for cleaning, and the borehole was staked for future land surveying.

4.3 BOREHOLE GEOPHYSICAL SURVEYS

Only the DWRC drilling method offers the opportunity for continuous wireline geophysical logging of a section without installing casing. Geophysical logs are an invaluable tool for environmental investigations when modeling plume geometry and distribution of sediments and predicting contaminant migration. Besides being used to supplement borehole lithologic logs, geophysical logs can be used to identify water-bearing horizons. However, the types of logs that can be successfully used with the DWRC drilling method are limited because the logs are run inside of the drill rods. Three types of logs were run during the investigation: (1) natural gamma radiation, (2) neutron, and (3) compensated density. Natural gamma radiation logs were run on all borings and on three existing monitoring wells. Neutron logs were run in selected borings (41 of 48). Compensated density logs were run as companion logs with the first six neutron logs. When used in combination with the gamma radiation and neutron logs, the density log generally adds to the interpretation of subsurface stratigraphy; however, the density logs run inside of the dual tube system appeared to be somewhat attenuated, and use of the tool was discontinued early in the investigation. Each log was run twice in each boring, and the results of each run were compared to ensure proper field operation.

4.4 WASTE HANDLING AND TRANSPORT

Waste generation from the DWRC drilling method consistently exceeded pre-project estimates due to the air lift pumping effect in water-bearing and heaving-sand zones. Additionally, when the air pressure was released to make pipe connections, the head differential between the unconsolidated formation and the inside of the drill string forced formation water up the inside of the drill string producing extra water and cuttings. The consistency of the cuttings was also very different from that of traditional drilling spoils generated from hollow stem auger drilling. The cuttings were produced as a slurry, and the waste management department at PGDP was not equipped to handle waste in slurry form. All waste had to be separated into solid and liquid fractions. Efforts to separate the liquid and solid fractions by gravity settling and flocculation were ineffective. Thus, a centrifuge-based material separation system was procured to separate the liquid and solid fractions of the cuttings.

Waste generated by the project consisted of 413 drums of drill cuttings in slurry form, two drums of personal protective clothing, 24 drums of miscellaneous field waste (plastic sheeting, etc.), one drum of field laboratory waste, and approximately 50,000 gal of purge water, wash water, and drilling fluid. The pre-project estimate for solid waste was about four drums per 150-ft borehole. The actual average for the project was about 7.7 drums per 150-ft borehole. The 350-ft boring produced 48 drums of drill cuttings due to heaving sands and abundant water in the McNairy Formation. The number of waste drums was reduced by 43% to 237 drums of drill cuttings after the drill cuttings were processed through the waste separation system. Discounting the drums from the 350-ft borehole, about 210 drums of cuttings for 47 boreholes or about 4.5 drums per 150-ft borehole were produced, which is very close to the pre-project estimate (Table 2).

Table 2. Solid waste drum record

	Number of drums prior to waste separation	Average number of drums per boring	Number of drums after waste separation	Average number of drums per boring after separation
Drums from 47 borings, 150 ft each	365	7.7	210	4.5
Drums from 1 boring 350 ft deep	48	48	27	27

The waste separation system consisted of three off-the-shelf units that, when run in series, were capable of separating solids from liquids down to about 5-μm particle size. The separation process was initiated by emptying the 55-gal drums of drilling spoils directly into a linear shale shaker and separating the first cut to 40 to 100 mesh. The processing continued with throughput to a mud cleaner consisting of several 4-in. hydrocyclones over a mini-shaker using 180 to 210 mesh screens. Effluent from the mud cleaner was treated by centrifuge in a high-volume/high-speed sequence that separated solids from liquids down to the 5-μm range. An 80-barrel agitated tank was used as a common compartmentalized holding vessel during the various phases. Pumps were used to circulate the effluent between the system components. The final effluent (liquid) and solids coming off the mud cleaner, shaker, and centrifuge were either pumped into polytanks (liquid) or stored in drums (solids). The waste was sampled for waste characterization, and the containers were subsequently turned over to waste management for processing or storage depending upon the results of waste sampling. After waste separation was completed, 237 drums of solid waste and 20,000 gal of water were turned over to PGDP waste management for processing and/or storage.

The biggest time limitation to waste separation was the feed rate for waste into the system and containerization and labelling of the output. The system was capable of processing over 25 gal/min, but only about 20 to 30 drums could be processed in a day because the drums had to be emptied individually into the system and solids recaptured in drums at three separate output locations. The cuttings were processed in batches to avoid mixing waste from different boreholes. Thus, it took approximately 25 days to process all of the drill cuttings generated by the investigation.

4.5 FIELD LABORATORY SUPPORT

Field laboratory support was provided by ORNL/GJ. Field screening of groundwater samples for volatile organic compounds (VOCs) was performed with a field gas chromatograph (GC). The analyses conformed with U.S. Environmental Protection Agency protocols for reconnaissance-level data. Informal reports of field analytical data and other field data were submitted weekly.

Each set of water samples was transported to the PGDP/ER sample log-in and storage area immediately after collection. A typical sample set included a set of triplicate 40-mL vials for the field laboratory, a set of duplicate 40-mL vials for the PGDP laboratory, and a set of samples for ^{99}Tc analysis. After being logged in, the samples for the field analysis were turned over to the ORNL field laboratory technician for analysis, while the other samples were transported to the PGDP laboratory for analysis. Triplicate samples were analyzed for VOC contamination in the field laboratory using a Hewlett Packard GC equipped with an electron capture detector. The GC was calibrated for the chlorinated solvents TCE and 1,2-dichloroethene (1,2-DCE). VOC sample preparation consisted of extracting 20 mL of the 40-mL zero-headspace sample and heating it at 50° C in a constant-temperature water bath for 30 min. The analysis was performed by using an auto sampler to withdraw a 100-μL aliquot of the headspace gas from the sample vial and inject it into the GC. The resulting chromatogram was compared to chromatograms of known standards. The results were reported in parts per billion (ppb); detection limits were 1.0 ppb for TCE and 5.0 ppb for 1,2-DCE.

5. EVALUATION OF FIELD METHODS

The FSP called for the use of DWRC drilling with overshot casing as the preferred method for this investigation. In theory the method offered several advantages over conventional hollow-stem auger drilling for environmental investigations. In practice, these advantages generally held true for this investigation, with the following observations:

1. The DWRC method was fast and efficient for drilling, and lithologic control was excellent. However, the groundwater sampling regime using a bladder pump and packer assembly was problematic and consumed the majority of the time spent on each boring.

2. The DWRC method seemed to adequately eliminate cross contamination, as demonstrated by the fact that in many instances, no water was being produced from a specific interval even after waiting for as much as two hours. However, by pulling the drill string up only a few feet to expose another zone, abundant water would enter the pipe, making sampling possible.

3. Sample results for groundwater obtained from intervals just a few feet apart often showed contaminants in one interval and none in the next, supporting the contention that cross contamination was not occurring.

4. Drill cutting volumes may approach theoretical hole size; however, the slurry produced by heaving sands and mixing of cuttings with groundwater and drilling water often increased volumes dramatically. PGDP waste management was not equipped to handle the resulting slurry and a dewatering system was mobilized to separate the liquids and solids. The dewatering system reduced the number of waste drums by 43%.

5. Geophysical logs were limited to those that could be performed inside a metal casing (i.e., radiation logs). However, attenuation by the metal casing was a factor for all logs, and density logs were of little use.

6. Pressure grouting worked very well and was relatively simple. The vertical distribution of contaminants and aquifers at PGDP made this a very desirable attribute in preventing cross contamination of aquifers.

In summary, the features of the drilling and sampling program that were problematical included:

- the slurry-like waste that required separation to solid and liquid fractions;
- attenuation of density logs, rendering them of little use;
- the bladder pump-packer method of sampling was slow, and the sampling pump often jammed due to sand heaving into the drill stem;
- the teflon bladders had to be replaced frequently;
- the packers were shown to be unnecessary if micropurging was used; and
- when drilling too rapidly in soft clay, the drill string would plug, requiring a trip to clear the blockage.

Changes made during the project or ones that should be considered for future projects are described below.

1. The bladder pump should be used without the packer assembly, and since the sample data generated is only reconnaissance level, a tygon bladder should be used instead of teflon to facilitate longer bladder life.

2. Micropurging should be used to reduce waste volume, speed up sampling, and eliminate the need for a packer.

3. At least three complete sampling set-ups should be clean and available for use at the start of each drilling day. This would help eliminate the standby time spent waiting for clean equipment.

4. Pea gravel should be inserted into the inner drill tube prior to sampling in zones where heaving sand is a problem to provide a crude filter for the sampling pump. This gravel would be expelled as soon as drilling resumed.

5. Waste separation down to clay-size particles should be performed on site by discharging from the cyclone directly onto a mini-shaker and hydrocyclone over a mud tank. The liquid effluent could then be hauled in poly-tanks to the centrifuge at the decontamination pad for final processing, and the solids would already be drummed for final disposition. This would eliminate emptying and refilling drums at the decontamination pad.

6. The use of overshot casing should be eliminated or else a Barber DWRC drilling rig that can advance the drill string and the casing simultaneously should be used.

7. Only gamma radiation and neutron logging tools should be used for downhole geophysics since the density logs were of little use.

8. Depth to the base of the RGA at each drilling location should be estimated and the driller instructed to slow down and inject water before drilling into the clays that may be present. This would reduce the chance of plugging the drill string with clay.

6. SUMMARY

Overall, the use of DWRC drilling with multi-level sampling succeeded in obtaining the data needed to achieve project goals. This approach allowed the investigation to be directed based on near-real-time data. Use of downhole geophysical logging in conjunction with lithologic descriptions of borehole cuttings resulted in excellent correlation of the geology in the vicinity of the contaminant plume. The total volume of cuttings generated using the DWRC drilling method was less than what would have been produced by hollow stem augering, but more than pre-project estimates. The drilling rate was very rapid, often approaching 10 ft/min; however, frequent breaks to perform groundwater sampling resulted in a slower overall average drilling rate. The time required for groundwater sampling could be shortened by changing the sampling methodology and having additional equipment on standby. Analytical results indicate that the drilling method successfully isolated the various water-bearing zones and that no cross contamination resulted from the investigation.

REFERENCES

Clausen, J. L., J. W. Douthitt, K. R. Davis, and B. E. Phillips. 1992. *Report of the Paducah Gaseous Diffusion Plant Groundwater Investigation Phase III*. KY/E-150. Martin Marietta Energy Systems, Inc., Paducah, Kentucky.

ERCE. 1990. *Recommended Soil Columns for Use in Amplification Studies, Paducah Gaseous Diffusion Plant, Paducah, Kentucky*. ERCE File No. B672. Prepared by ERC Environmental and Energy Services Co., Inc., for Paducah Gaseous Diffusion Plant, Martin Marietta Energy Systems, Inc., Paducah, Kentucky.

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