

Prepared in cooperation with the
U.S. Air Force, Aeronautical System Center

Design and Operation of a Borehole Straddle Packer for Ground-Water Sampling and Hydraulic Testing of Discrete Intervals at U.S. Air Force Plant 6, Marietta, Georgia



Open-File Report 2008–1349

Cover. Straddle-pack system deployment at U.S. Air Force Plant 6, Marietta, Georgia, 2004.

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By Owen G. Holloway and Jonathan P. Waddell

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

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Conversion Factors

Multiply	By	To obtain
Length		
inch	2.54	centimeter (cm)
inch	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m ²)
Volume		
gallon (gal)	3.785	liter (L)
cubic foot (ft ³)	28.32	cubic decimeter (dm ³)
Flow rate		
gallon per minute (gal/min)	0.06309	liter per second (L/s)
Pressure		
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)
inch of mercury at 60°F (in Hg)	3.377	kilopascal (kPa)
pound-force per square inch (lbf/in ²)	6.895	kilopascal (kPa)

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

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Vertical coordinate information is referenced to the insert North American Vertical Datum of 1988 (NAVD 88).

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

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (μg/L).

Design and Operation of a Borehole Straddle Packer for Ground-Water Sampling and Hydraulic Testing of Discrete Intervals at U.S. Air Force Plant 6, Marietta, Georgia

By Owen G. Holloway and Jonathan P. Waddell¹

Abstract

A borehole straddle packer was developed and tested by the U.S. Geological Survey to characterize the vertical distribution of contaminants, head, and hydraulic properties in open-borehole wells as part of an ongoing investigation of ground-water contamination at U.S. Air Force Plant 6 (AFP6) in Marietta, Georgia. To better understand contaminant fate and transport in a crystalline bedrock setting and to support remedial activities at AFP6, numerous wells have been constructed that include long open-hole intervals in the crystalline bedrock. These wells can include several discontinuities that produce water, which may contain contaminants. Because of the complexity of ground-water flow and contaminant movement in the crystalline bedrock, it is important to characterize the hydraulic and water-quality characteristics of discrete intervals in these wells. The straddle packer facilitates ground-water sampling and hydraulic testing of discrete intervals, and delivery of fluids including tracer suites and remedial agents into these discontinuities.

The straddle packer consists of two inflatable packers, a dual-pump system, a pressure-sensing system, and an aqueous

injection system. Tests were conducted to assess the accuracy of the pressure-sensing systems, and water samples were collected for analysis of volatile organic compound (VOCs) concentrations. Pressure-transducer readings matched computed water-column height, with a coefficient of determination of greater than 0.99. The straddle packer incorporates both an air-driven piston pump and a variable-frequency, electronic, submersible pump. Only slight differences were observed between VOC concentrations in samples collected using the two different types of sampling pumps during two sampling events in July and August 2005. A test conducted to assess the effect of stagnation on VOC concentrations in water trapped in the system's pump-tubing reel showed that concentrations were not affected. A comparison was conducted to assess differences between three water-sampling methods—collecting samples from the well by pumping a packer-isolated zone using a submersible pump, by using a grab sampler, and by using a passive diffusion sampler. Concentrations of tetrachloroethylene, trichloroethylene and 1,2-dichloropropane were greatest for samples collected using the submersible pump in the packed-isolated interval, suggesting that the straddle packer yielded the least dilute sample.

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Introduction

U.S. Air Force Plant 6 (AFP6) in Marietta, Georgia, is a government-owned, contractor-operated, military-aircraft fabrication and repair facility. As part of the operations at AFP6, large quantities of petroleum fuels, oils, lubricants, chlorinated solvents, and protective coatings are used. Past manufacturing practices have resulted in the release of volatile organic compounds (VOCs), primarily trichloroethylene (TCE), tetrachloroethylene (PCE), and benzene, along with semivolatile organic compounds (SVOCs) and metals into the soil and ground water at the plant. In 1995, dissolved TCE was detected in a ground-water sample collected from a new, but unused, irrigation well located at Southern Polytechnic and State University, indicating that VOCs may have migrated from AFP6 (Stewart, 2000). Studies indicate that ground-water contaminants are transported through discontinuities in the otherwise impermeable crystalline bedrock. These discontinuities can include fractures, joints, faults, contacts between rock bodies, shear zones, and bedding planes (Williams and Others, 2004).

The U.S. Geological Survey (USGS)—in cooperation with the U.S. Air Force, Aeronautical System Center—conducted a multidiscipline, field-based study to better understand contaminant fate and transport in a crystalline bedrock setting and to support remedial activities at AFP6. Numerous wells that have long open-hole intervals in the crystalline bedrock have been constructed at and near the site. Each well can include several discontinuities that produce water, which may contain contaminants. Because of the complexity of ground-water flow and contaminant movement in the crystalline bedrock, it is important to characterize the hydraulic and water-quality characteristics of discrete intervals within these open-hole wells.

Purpose and Scope

The purpose of this report is to (1) describe the design and operation of a straddle packer for open-hole wells; and (2) assess the performance of the straddle packer, including its pressure-sensing system and its ability to collect representative water-quality samples. The straddle packer facilitates

ground-water sampling and hydraulic testing of discrete intervals and delivery of fluids, including tracer suites and remedial agents, into discrete discontinuities.

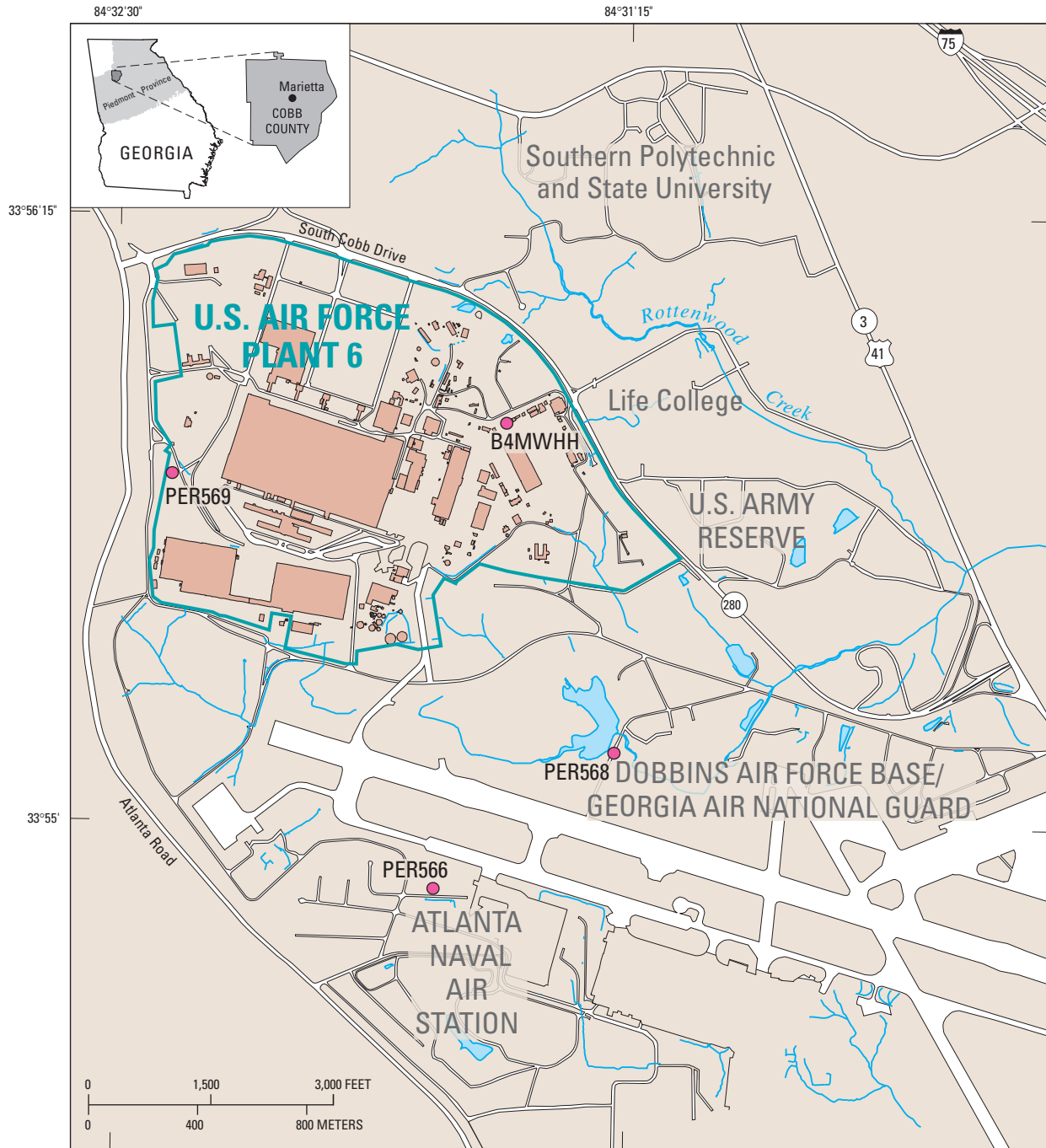
The straddle-packer design phase lasted from March 2004 to September 2004. Testing and analysis of the straddle packer within AFP6 wells began in late September 2004 and ended in October 2006. Straddle packer operation protocols have been refined from previous investigations (Stewart, 2000), and experiences with the redesigned straddle packer through September 2005 have led to further improvements.

Description of Study Area

AFP6 covers about 720 acres and is part of a military complex that includes Dobbins Air Force Base, the Atlanta Naval Air Station, the U.S. Army Reserve, and the Georgia Air National Guard (fig. 1). The plant was constructed in 1942 to support production of B-29 “Superfortress” aircraft during World War II. Lockheed Martin Aeronautical Systems Corporation has operated AFP6 for the U.S. Air Force as an aircraft production and modification facility since 1951. AFP6 is located in the Central Uplands district of the Piedmont Province of north Georgia (Fenneman, 1938). Topography consists of low northeast-trending ridges separated by valleys, with altitudes ranging from approximately 950 to 1,100 feet (ft).

The subsurface beneath AFP6 consists of saprolite overburden that grades downward to partially weathered rock (transition zone) underlain by crystalline bedrock at depth (fig. 2). AFP6 is underlain by bedrock of the Powers Ferry Member of the Stonewall Gneiss (Crawford and others, 1999) consisting of biotite-plagioclase gneisses, aluminous schists, and amphibolites (Higgins and others, 1988).

At AFP6, the general flow of ground water follows the topographic contours of the land surface (International Technology Corporation, 1999) through the overlying saprolite overburden, flowing downward into the transition zone and entering a network of discontinuities in the crystalline bedrock (fig. 2). Although these discontinuities represent different features such as fractures, faults, and bedding planes, not all discontinuities form a flow path for ground-water movement within the system.



Base modified from U.S. Geological Survey
Marietta 1:24,000, 1992

EXPLANATION

- Boundary of U.S. Air Force Plant 6
- PER566 ● Well and identification number
- Building

Figure 1. Location of U.S. Air Force Plant 6, test wells, and buildings, Marietta, Georgia.

4 Design and Operation of a Borehole Straddle Packer for Ground-Water Sampling

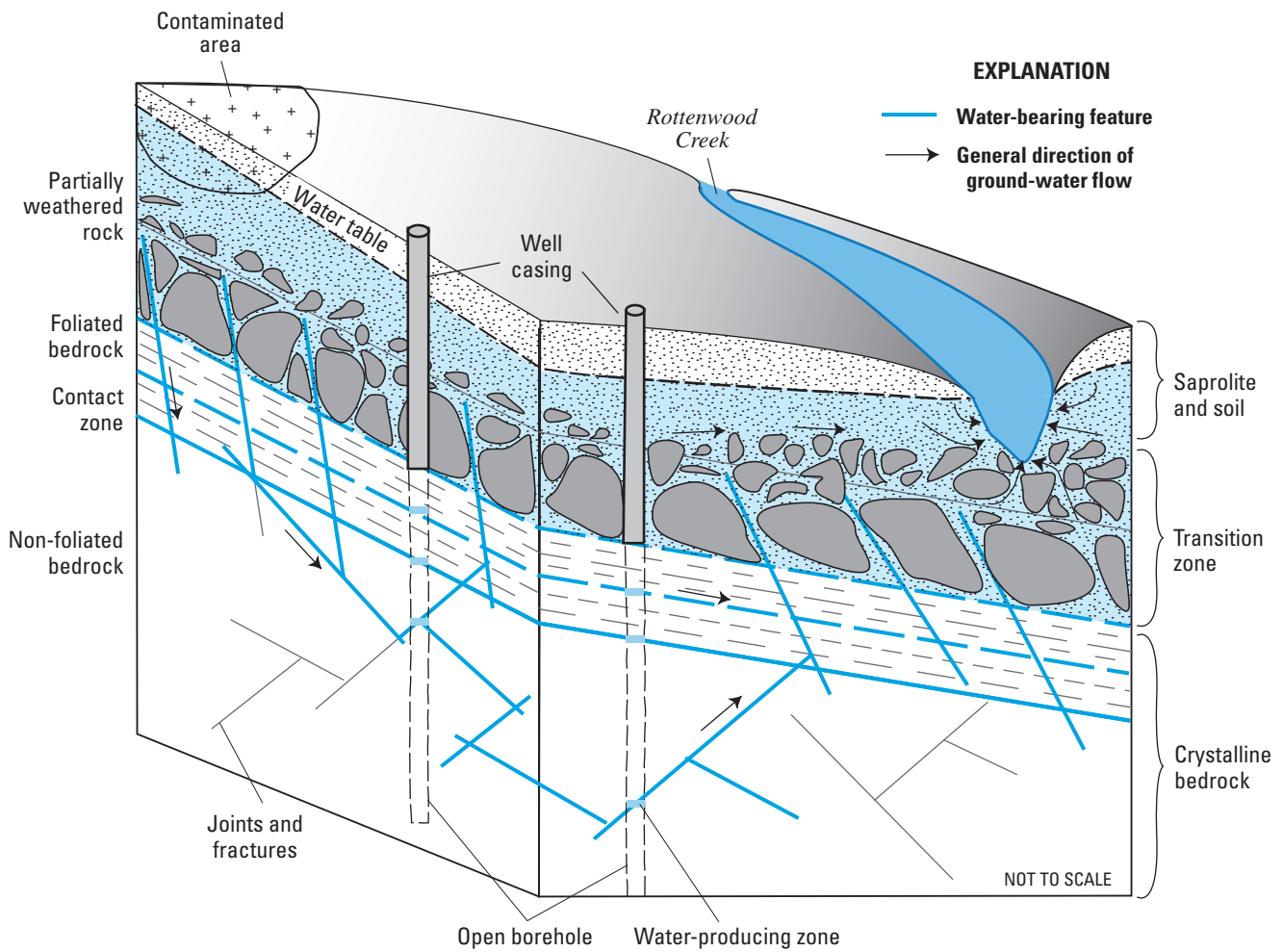


Figure 2. Schematic diagram showing hydrogeologic setting, U.S. Air Force Plant 6, Marietta, Georgia.

Method of Study

As part of remedial investigations at AFP6, several types of wells were constructed on and off site. These wells included shallow screened wells completed in the saprolite, screened wells completed in the transition zone between the saprolite and the crystalline bedrock, and open-hole wells completed in the crystalline bedrock (fig. 3). The open-hole crystalline bedrock wells were completed by drilling a boring through the saprolite and transition zone, installing well casing, and then drilling an open-hole into the crystalline bedrock. These open-hole intervals commonly were hundreds of feet in length, and included several water-bearing discontinuities. To characterize the hydraulic and water-quality characteristics of these intervals, a straddle packer was designed and used to characterize discrete zones in the crystalline bedrock.

An assessment of potential water-bearing intervals in the open-hole wells was made by conducting borehole geophysical surveys. The straddle packer was designed, constructed, and used to isolate discrete intervals in the open-hole wells. Water samples and measurements of hydraulic properties, such as head, were collected at each discrete interval. Water samples

were sent to a USGS Department of Defense Earth Science Program contract laboratory and analyzed for analytes indicative of in situ VOC contamination. Head was measured in situ using pressure transducers integrated into the straddle packer.

Straddle-Packer Design

The straddle packer designed for AFP6 was used to measure the hydraulic head of discrete discontinuities, conduct hydraulic and tracer tests, and collect ground-water samples for water-quality analysis. Use of packers and straddle packers for isolation and characterization of discrete discontinuities within crystalline bedrock has been described by the American Society for Testing and Materials (1995) and the U.S. Environmental Protection Agency (1996). The AFP6 straddle packer improves upon earlier designs by (1) decreasing susceptibility to electrical failure by deployment under high hydrostatic pressure; (2) facilitating ground-water sample collection and hydraulic testing of openings characterized by varying degrees of transmissivity; and (3) operating at depths as great as 600 ft below land surface.

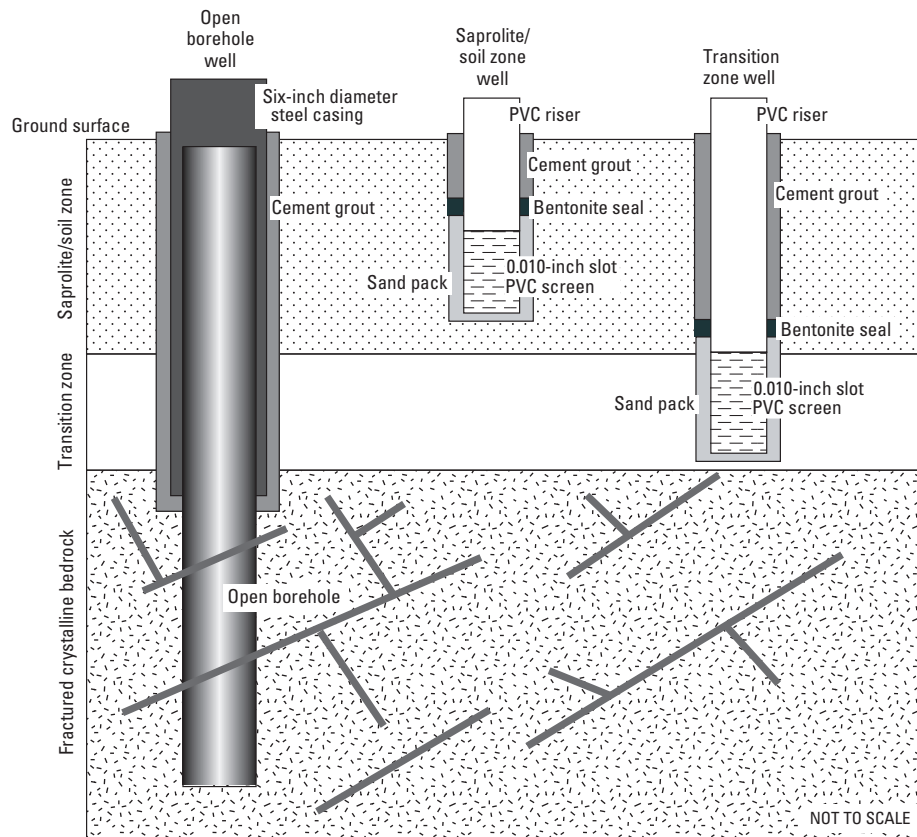


Figure 3. Schematic diagram showing well construction and generalized geology, U.S. Air Force Plant 6, Marietta, Georgia (modified from Stewart, 2000). [PVC, polyvinyl chloride]

Early Straddle Packers

Straddle packers have been developed and used by USGS researchers since the early 1960s (Jones, 1961). The typical, modern straddle-packer design (fig. 4) includes two inflatable packers outfitted with three transducers to monitor pressure above, between, and below the packers (Hsieh and others, 1985). Pressure transducers monitor the hydrostatic pressure to a maximum of 200 pounds per square inch (psi) and record outputs between 0 and 50 millivolts using a data logger (Hsieh and others, 1993).

For long-term, multilevel monitoring of hydraulic heads, Hsieh and others (1993, 1996) developed straddle packers with tubes extending from each isolated interval to land surface, where interval-specific water levels could be measured. Later straddle packers were outfitted with a fluid-injection valve and submersible pump within the middle interval for injection tests and ground-water sample collection (Hsieh and others, 1993; Shapiro and Hsieh, 1998; Stewart, 2000; Shapiro, 2001).

Of the systems previously noted, none fulfilled the need of the AFP6 project. Previous designs had either depth or sampling limitations. Several of the open-hole wells at AFP6 were 600 ft deep, and the permeability of the discontinuities was unknown. Lift criteria from other systems using small, electric, submersible pumps could not sample at these depths. Designs that used large, electric, submersible pumps could not be controlled for low-flow VOC sampling. Using an existing straddle packer with only one sample pump would not allow for data collection from zones with either high or low permeability. Other designs that were reviewed rely on the middle and lower pressure transducers being installed at the top of the system and using drop tubes to convey water to the sensors. Pneumatic valves must be installed and activated to release trapped air in the lines prior to measurements. Prototypes of the AFP6 straddle-packer used this technology but proved to be cumbersome in deployment and unreliable for measurements. Making changes in the straddle packer to overcome these shortfalls led to the design of a system that better suited the needs at AFP6.

Design of AFP6 Straddle-Packer Systems

The straddle packer developed for the AFP6 project includes up-hole components and the down-hole straddle packer. Up-hole components support the straddle packer during down-hole use and include a water-quality trailer, mobile pump hoist, and tubing and cable reel assembly trailer (fig. 5). All pneumatic and electrical controls for the straddle packer are contained within the water-quality trailer. The straddle packer consists of two inflatable packers, a dual-pump system, a pressure-sensing system, and an aqueous-injection system. Some of these components were adapted from previous straddle packers. The dual-pump system allows for a broad range of pumping rates at various depths. The air-driven piston pump allows for low-flow VOC col-

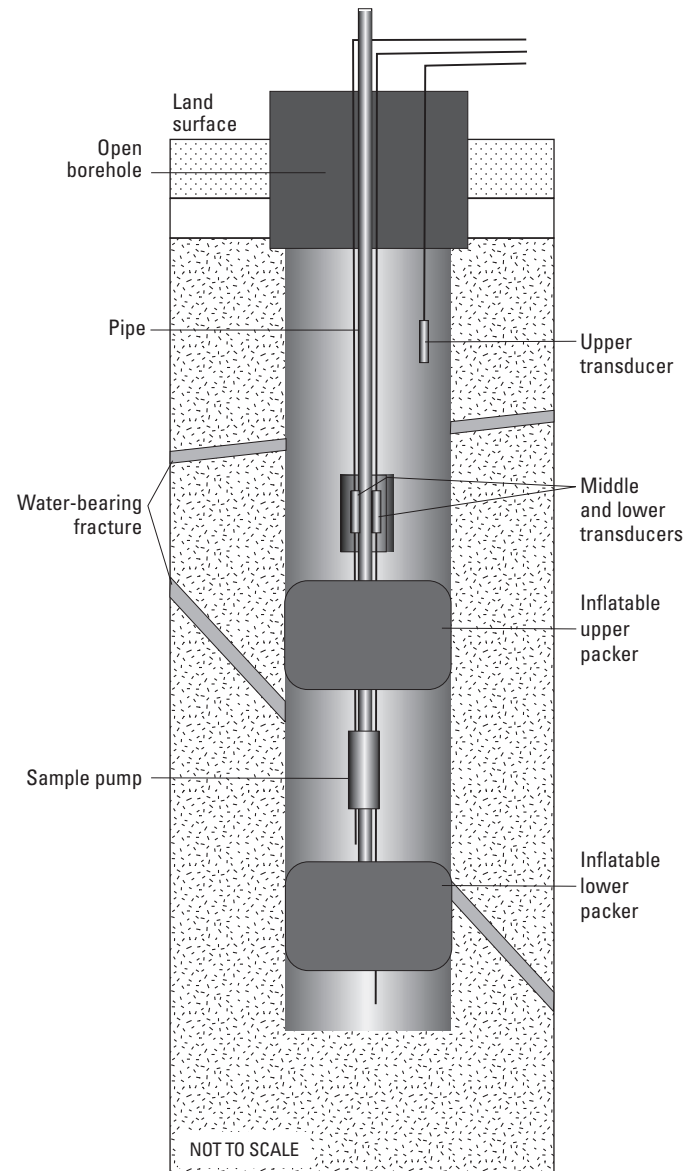


Figure 4. Schematic diagram showing a typical modern straddle packer installed in a well (modified from Stewart, 2000).

lection and purging of low permeability intervals, while the electric variable-controlled submersible pump can remove greater purge volumes from intervals of high permeability and still have the capability to reduce discharge for collection of VOCs. Collapsing drop tubes and trapped air within the pressure-sensing system were addressed by physically locating the pressure transducers within the tool instead of mounting the transducers above the packers. All down-hole electrical components such as cables, connections, and splices within the straddle-packer body were selected based upon their ability to withstand hydrostatic pressure changes within the ranges of operational depths.

Water-Quality Trailer

The custom-built water-quality trailer is self-contained and was designed to support field operations for extended lengths of time (fig. 6). The trailer is equipped with an onboard 8,000-watt generator providing 110 and 220 alternating current (AC) service to meet the power needs of the

electric submersible pump, computers, lights, compressor, heating and cooling, and analytical equipment. Installed on the roof is a 750-watt solar panel that is linked to a bank of 12-volt batteries that supply constant energy for dataloggers. The water-quality trailer houses a straddle-packer control box, a variable-frequency-drive (VFD) controller, and a ground-water sample-collection chamber.



Figure 5. Components of AFP6 straddle-packer system, U.S. Air Force Plant 6, Marietta, Georgia.



Figure 6. Interior of water-quality trailer. The tank to the right contains deionized water used for borehole injections.

8 Design and Operation of a Borehole Straddle Packer for Ground-Water Sampling

The straddle-packer control box, custom-built from stainless steel, houses two separate pneumatic delivery systems, a barometer, three precision flowmeters, and a

Campbell Scientific® CR23X datalogger (fig. 7). The first pneumatic delivery system is used to distribute compressed air to the upper packer, the lower packer, a down-hole injection

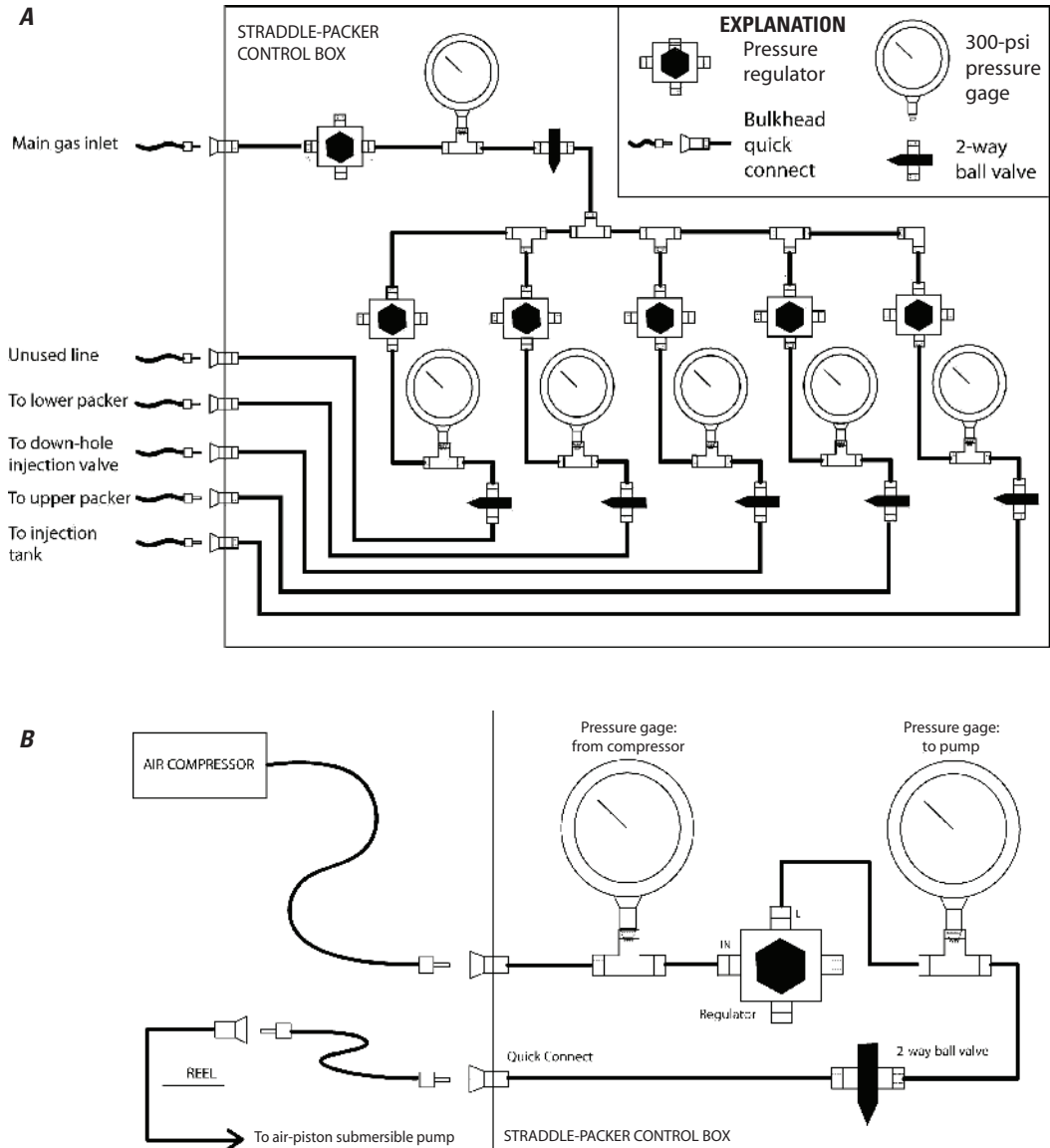
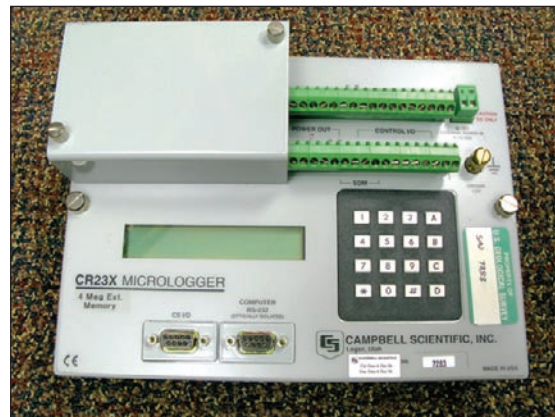


Figure 7. Components of control box for AFP6 straddle packer: (A) first pneumatic delivery system used to provide compressed gas to packers, injection valve, and injection tank; (B) second pneumatic delivery system used to provide compressed air to dual-pump system; (C) Campbell Scientific CR23X datalogger.



valve incorporated into the straddle packer, and a 40-gallon injection tank. The second pneumatic delivery system is used to deliver compressed air to the dual-pump system.

The barometer was factory-calibrated to measure atmospheric pressure from 0.6 to 1.06 millibars and to output voltage measurements via switched excitation outputs. Barometric-pressure measurements are recorded on the CR23X datalogger.

Three stainless-steel turbine flowmeters have been permanently installed in the straddle-packer control box. The first flowmeter is used to measure ground-water purging rates from 0.25 to 10 gallons per minute (gal/min). The remaining two flowmeters are used to measure flow rates from fluid injection for extended ranges of 0.01 to 0.4 gal/min and 0.05 to 2.0 gal/min. Each flowmeter has been factory-calibrated and comes with a certificate of calibration and conformance.

Radio frequency output from each flowmeter is converted to pulse output by a carrier amplifier and input into the datalogger where data are stored in raw and calibrated formats. The datalogger can store up to 4 megabytes of data

from analog (single-ended and differential) inputs, pulse-counting channels, digital input/output ports, analog outputs, and switched excitation outputs and can be connected with an RS-232 port to a personal computer where data may be displayed or downloaded.

The custom-built, ground-water sample-collection chamber (fig. 8) facilitates the collection of filtered and unfiltered ground-water samples with concurrent observation of field properties (pH, specific conductance, temperature, and dissolved oxygen). The wall-mounted, open-faced chamber is constructed of stainless steel and includes three separate discharge lines. As illustrated in figure 8, the first valved line on the left is composed of rigid fluorinated ethylene propylene (FEP) and is used to collect unfiltered samples. The middle valved line incorporates a flexible silicon-based tubing to attach an in-line 0.45-micron filter. A YSI® 556 multi-parameter probe, with a flow cell to monitor field properties, is attached to a corrugated FEP line located on the far right side of the collection chamber.

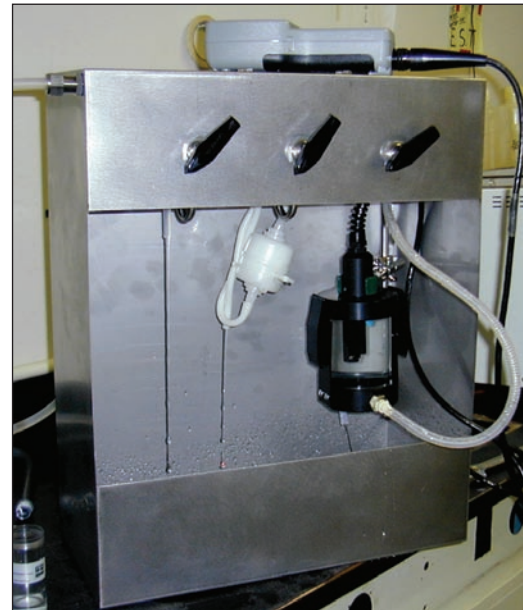
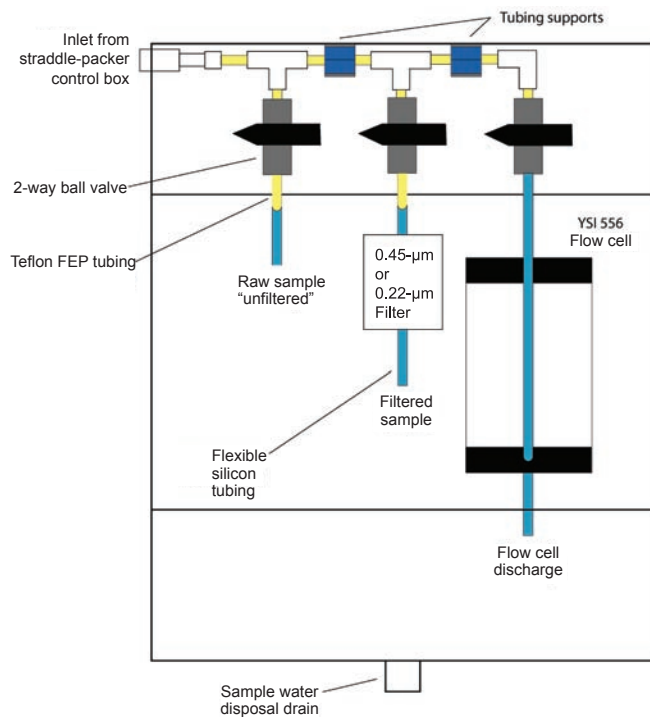


Figure 8. Schematic diagram and photograph showing ground-water sample-collection chamber for AFP6 straddle packer. [FEP, fluorinated ethylene propylene; µm, micrometer]

Tubing and Cable Reel Assembly and Trailer

A transportable trailer was outfitted with three hose reels and a 100-gallon tank for investigation-derived waste collection (fig. 9), and storage of AQ (1.75-inch) drill rod used to raise and lower the straddle packer into the well (not shown). The discharge tubing reel holds approximately 600 ft of 5/8-inch outside diameter (OD) FEP tubing (fig. 10). This tubing is used to transport ground water pumped at depth by the dual-pump system to the sample-collection chamber, or to inject fluid from the injection tank into the isolated interval. The second reel contains 600 ft of power cable for the electrical submersible pump. The third reel accommodates two 1/4-inch (OD) nylon pneumatic packer inflation lines, two 1/2-inch (OD) nylon pneumatic lines for the air piston pump, a 1/4-inch (OD) pneumatic line to actuate a down-hole pneumatic injection valve, and 600 ft of transducer cable. All tubing and cables within the first and third reels have been

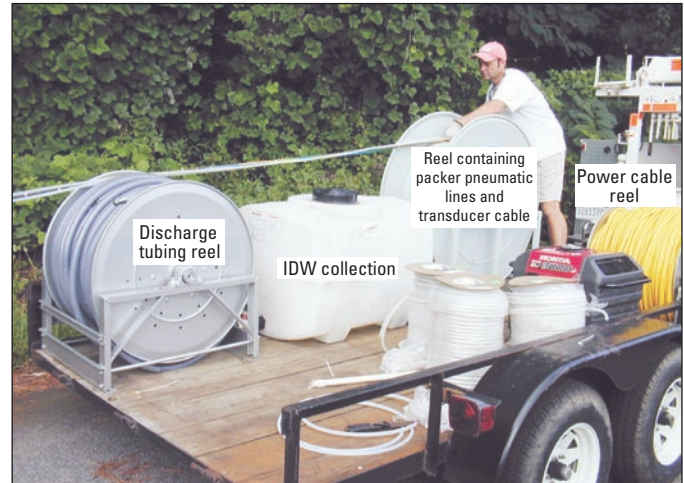


Figure 9. Tubing/cable reel assembly for AFP6 straddle packer. [IDW, investigation derived waste]

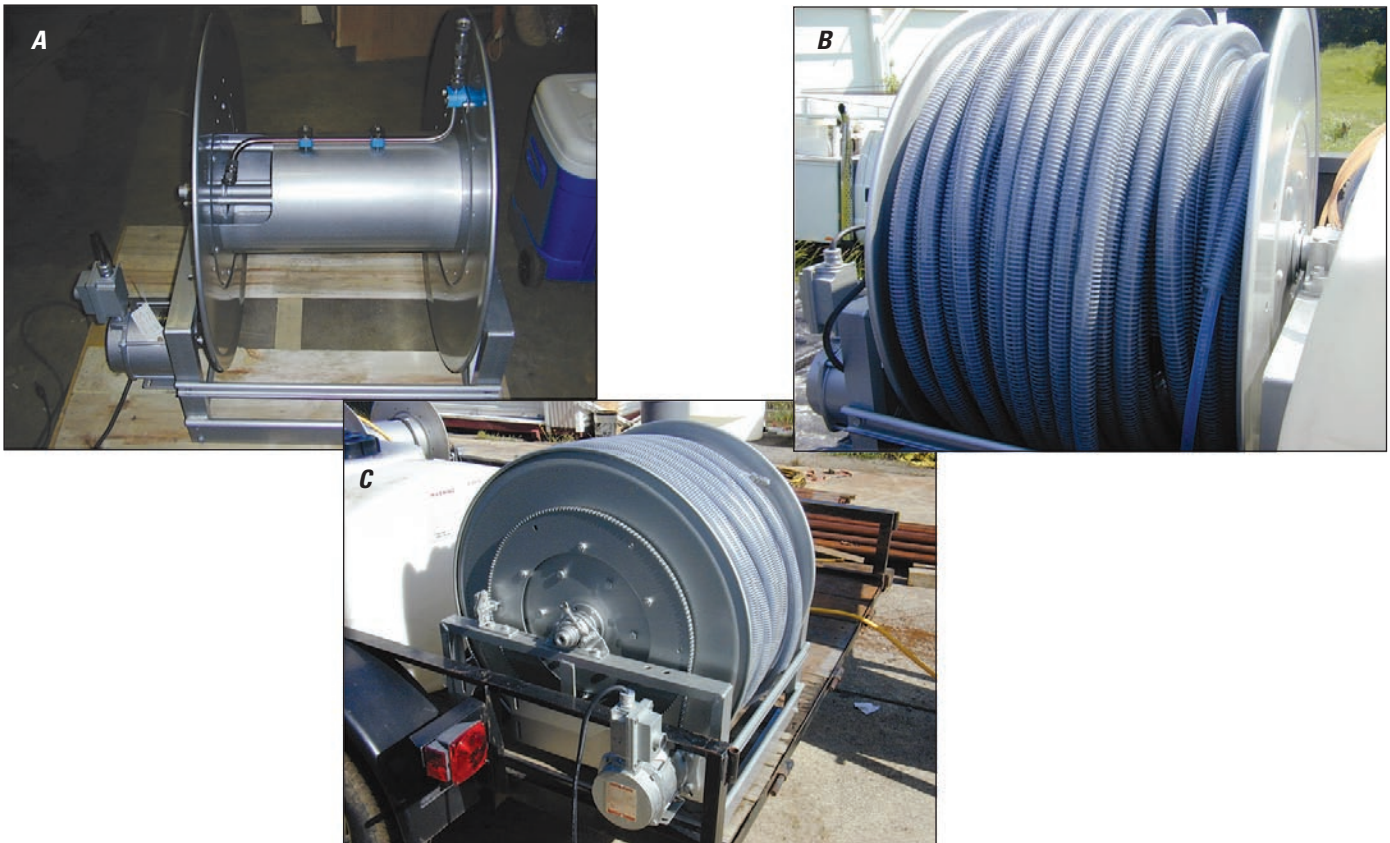


Figure 10. Discharge tubing reel for AFP6 straddle packer: (A) reel skeleton, (B) loading of discharge tubing sheathed within clear PVC-reinforced vacuum tubing onto reel, (C) placement of reel on tubing/cable reel assembly trailer.

enclosed within polyvinyl chloride (PVC) reinforced tubing for protection against abrasion during deployment. The reels were positioned upon the trailer to best distribute weight and allow ease of tubing deployment and retrieval down hole.

Inflatable Packers

The AFP6 straddle packer consists of two inflatable packers that may be positioned above and below a sampling interval (fig. 11). The straddle packer was designed and built to be used in 6-inch-diameter boreholes. Both packers are composed of a stainless-steel skeleton (mandrel) enveloped within a malleable-rubber gland, rubber shoulders, retaining rings, and lock nuts on each end. The stainless-steel components such as mandrels, retaining rings and lock nuts, were custom-built. All non-metallic components were obtained from the Roctest Telemac product line of YEP® 4.75-inch fixed-head packers. Each mandrel has a stainless-steel head at each end, through which tubing and cables pass. Specifically, the heads of the upper packer were drilled and tapped to accommodate two 1/2-inch (OD) pneumatic lines, one 5/8-inch (OD) discharge line, three 1/4-inch (OD) pneumatic lines, a single transducer cable, and a power-supply cable for the electrical submersible pump (fig. 12). The lower packer heads, alternatively, were drilled and tapped for one 1/4-inch (OD) packer inflation line and a transducer cable. Stainless-steel tubing is used for all tubing passed through the upper packer. Electrical splices made within each packer are immobilized within a polymer resin to protect against introduction of air. Individual wires are jacketed with heat-shrink tubing to prevent damage from packer under-inflation under high hydrostatic pressures. Packers are inflated using compressed air from two 300-cubic-foot air tanks located in the water-quality trailer. Figure 13 shows photographs of the packer assembly. The minimum interval distance of 8.6 ft is limited by the length of the pump shroud located between the upper and lower packers. The interval can be lengthened by adding sections of 1-inch black pipe between the bottom of the shroud and the top of the lower packer. Transducer cables were fabricated for various lengths to accommodate these extensions.

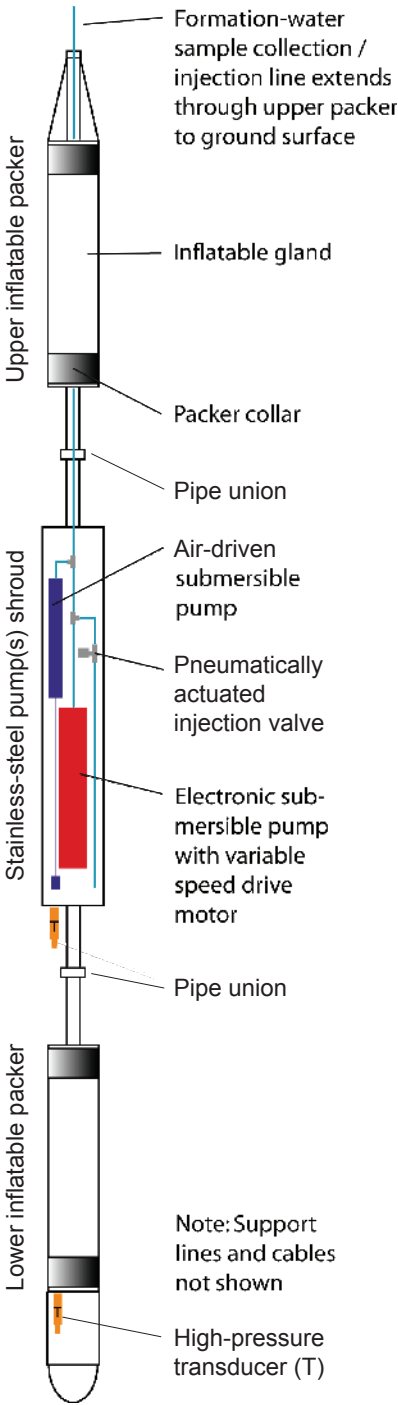


Figure 11. Schematic diagram of AFP6 straddle packer.



Figure 12. Head of upper packer showing custom drilled and tapped holes to accommodate two 1/2-inch pneumatic lines, one 5/8-inch discharge line, three 1/4-inch pneumatic lines, a single transducer cable, and a power-supply cable for the electrical submersible pump, AFP6 straddle packer.



Figure 13. AFP6 straddle packer: (A) middle transducer situated between shroud and lower packer, (B) tubing and cable connections between middle packer and shroud, and (C) down-hole tubing affixed to drill rod during packer deployment.

Dual-Pump System

The dual-pump system includes a Bennett 1800-8 air-driven piston pump and a Grundfos® Redi-Flo4® model 5E17 variable frequency drive (VFD) electric submersible pump (fig. 14). Both submersible pumps are stabilized on a custom-built stainless-steel frame that is housed within a 5.6-ft-long, 4.75-inch (OD) stainless-steel shroud situated between the packers. The shroud protects the pumps, a down-hole injection valve, and transducer cables during deployment. Discharge from both submersible pumps is lifted through 5/8-inch (OD) FEP tubing to land surface. A turbine flowmeter (see *Water-Quality Trailer* section) is used to measure pumping rates between 0.25 and 10.0 gal/min.

The air-driven piston pump is incorporated into the straddle-packer configuration for purging and sampling of low-production intervals at rates less than 2 gal/min. The pump is actuated by simultaneous delivery and exhaust of compressed air. An air compressor capable of air-flow delivery up to 5 cubic feet per minute (ft³/min) is required. The pump is situated within the upper portion of the shroud, with an extension placed between the pump body and the pump intake (located at the bottom of the shroud) to facilitate a more complete interval purge.

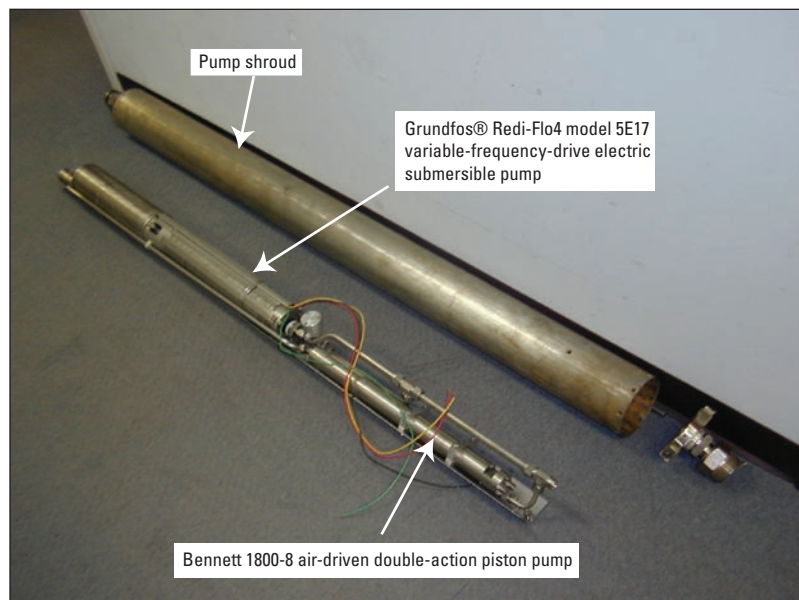
The electric submersible pump is equipped with a 2-horsepower VFD motor and is used to sample high-production intervals, generally at rates between 1.2 and 7 gal/min. The use of a VFD motor allows for lower flow and greater depth pumping capabilities by having the ability to increase or decrease lift. The VFD motor of the electric submersible pump is controlled using a control box located at land surface (previously described) and requires a 220-volt AC input.

Pressure-Sensing System

Two Druck® PTX 1830 pressure transducers, capable of measuring pressure up to 200-pound force per square inch absolute (psia), are incorporated in the straddle-packer body to monitor hydraulic heads within the isolated interval and below. All transducers are mated and spliced to cables with water-tight male/female connectors to allow for easy replacement. The middle interval transducer is positioned directly beneath the pump shroud and above the collar of the lower packer (fig. 13A). The bottom transducer is situated directly underneath the lower packer collar and is protected within a steel guide cone. Pressure in the upper interval is monitored using a Druck® PTX 1830 50-psia pressure transducer that is lowered into the well after deployment. Regardless of operating pressure, all transducers receive an excitation voltage between 9 and 30 volts direct current and return a current output between 4 and 20 milliamps (mA). The milliamp signal is converted to an absolute pressure reading using the factory calibration. Absolute pressure is converted to gauge pressure in pound-force per square inch gauge by subtracting out the barometric pressure monitored at the land surface with the Vaisala® PTB101 analog barometer. Outputs from the pressure transducers are input into and stored within the datalogger. All data are stored in both raw and calibrated formats.

Absolute pressure transducers were selected for use instead of vented pressure transducers because with absolute transducers, a vent tube does not need to be connected to the atmosphere. Vent tubes can collect condensation as a result of raising and lowering the straddle packer within the well and may clog the transducer line, inadvertently affecting transducer measurements. Also, the use of the datalogger and support software allows for simultaneous collection of absolute pressure and gauge pressure, which is obtained by subtracting out the barometric pressure measured at the land surface.

Figure 14. Dual submersible pump system for AFP6 straddle packer.



Aqueous Injection System

To facilitate injection and falling-head slug tests, a stainless-steel bellows-sealed valve with an actuator has been installed within the straddle-packer shroud. The actuator, which is normally closed, is activated with a pneumatic slug that is 100 psi greater than the hydrostatic head on the valve. The injectant, stored within a pressurized water tank (fig. 6), is delivered through an in-line flow indicator, one of two turbine flow meters, and into the interval by way of the discharge tubing. The in-line flow indicator is used to record the moment that injectant begins to flow from the tank into the middle interval. The flow ranges of the injection valves have been staggered for increased accuracy at low and high injection pressures—0.01 to 0.40 gal/min and 0.05 to 2.0 gal/min. One-way check valves are installed above each submersible pump to ensure that the injectant does not pass through the pumps.

AFP6 Straddle-Packer Operation

Operation of the straddle packer includes:

- deployment to an identified interval,
- isolation of the interval by packer inflation,
- interval purging and collection of a ground-water sample,
- testing of hydraulic properties by pumping, injection and/or slug tests, and
- decontamination of the straddle packer.

Standard operating procedures for each of these steps are described below.

Deployment of Straddle Packer

Deployment of the straddle packer is based on previously collected geophysical data to identify target deployment locations and interval lengths. The AFP6 straddle packer can be adjusted to isolation-interval lengths to accommodate varying size intervals, with a minimum interval of 8.6 ft. After components of the straddle packer have been assembled and before it is lowered into the well, all systems are diagnostically tested to ensure that the straddle packer is operational. The straddle packer is lowered until the two packers encompass the target interval. During deployment to an interval, transducer readings are monitored to validate depth and to ensure accuracy of placement. As deployment depth increases, straddle-packer pressure must be adjusted to overcome hydrostatic pressure, thus preventing over or under inflation of the packer bladder and damage from the borehole wall. Ambient pressure is calculated independently for the upper and lower packer by

estimating the hydrostatic head of fluid above each packer in feet using the following equation:

$$\text{Hydrostatic Head (feet)} = \text{Depth of Packer (feet below land surface)} - \text{Depth to Water (feet below land surface)} \quad (1)$$

Hydrostatic head for each packer is then converted to pressure using the following conversion equation:

$$\text{Hydrostatic Head (pounds per square inch @ 60°F)} = \text{Hydrostatic Head (feet)} / 2.30897 \quad (2)$$

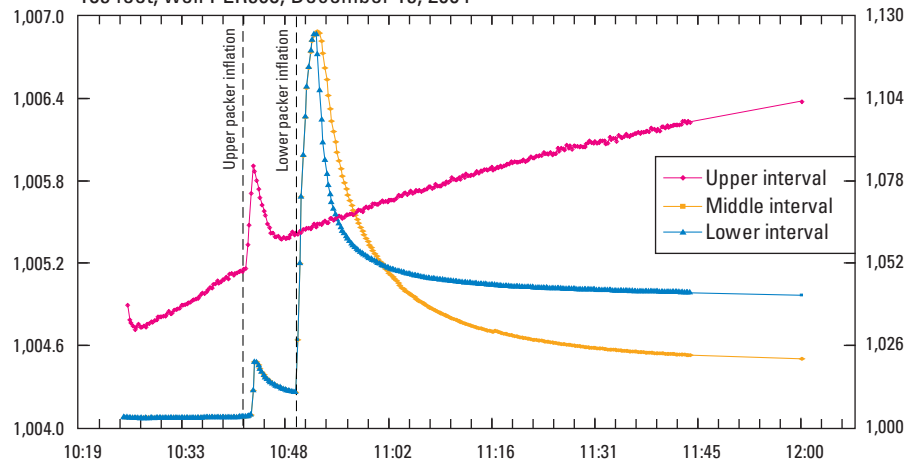
Isolation of Interval

The first step of isolation is to ensure that both the upper and lower packers are at or near ambient hydrostatic pressure, which increases as the straddle packer is lowered beneath the water surface within the well. Isolation of the interval of interest is achieved by inflating each packer to a pressure that is equal to the hydrostatic head plus the packer inertia pressure and seating pressure. According to the manufacturer of the packers, the packer inertia pressure, which is the pressure needed to expand the packer to its maximum diameter, and the packer seating pressure are 29 psi and 50 psi, respectively, as indicated in the following equation:

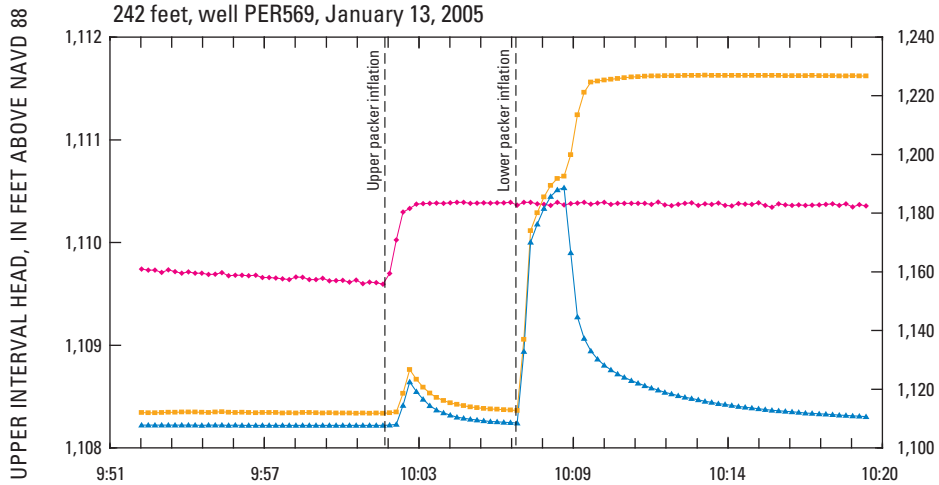
$$\text{Head (psi)} + 29 \text{ (psi)} + 50 \text{ (psi)} = \text{Isolation Pressure} \quad (3)$$

Packer inflation is gradual, not instantaneous. The upper packer generally is inflated first, followed by inflation of the lower packer (Lewis-Brown and others 2005). Pressure is recorded by the transducers located above, below, and within the middle interval as the packers are inflated. Following inflation of the upper packer, pressure measurements are recorded for each transducer until values stabilize, then the lower packer is inflated and the pressure monitored until values stabilize. The pressure response in the middle transducer following inflation of the two packers provides an indication of the hydraulic conductivity of the interval—rapid recovery following inflation indicates high permeability and a slow recovery indicates low permeability (fig. 15A,B). For instance, the inflation of the lower packer at 242 ft in PER569 caused over-pressurization of the middle interval (fig. 15B). Failure of the pressure to restabilize in the interval indicates a low-permeability zone. Additionally, inflation of the lower packer also may identify a hydraulic leak within intervals as indicated by a pressure change in the upper transducer following inflation of the lower packer (fig. 15C). If pressure changes within the interval do not need to be observed during inflation, the sample chamber located in the water-quality trailer can be opened. Water in the interval can escape by way of the electric submersible pump, through the sample line to land surface, thus relieving the pressure of the interval.

A. Middle interval recovery following inflation of upper and lower packers, 185 feet, well PER568, December 15, 2004



B. Lack of middle interval recovery following inflation of upper and lower packers, 242 feet, well PER569, January 13, 2005



C. Packer leakage as indicated by upper interval response to inflation of lower packer, 367 feet, well PER566, October 7, 2004

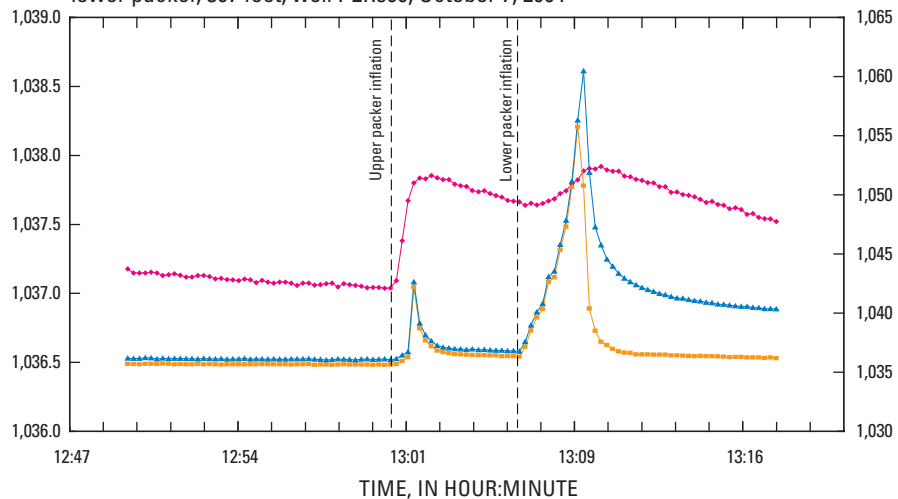


Figure 15. Head response in upper, middle, and lower intervals, (A) well PER568, (B) well PER569, and (C) well PER566, U.S. Air Force Plant 6, Marietta, Georgia. See figure 1 for well locations.

MIDDLE AND LOWER INTERVAL HEADS, IN FEET ABOVE NAVD 88

Interval Purging and Ground-Water Sample Collection

Following deployment of the AFP6 straddle packer and isolation of the interval, a water sample can be collected using the dual-pump system. To ensure a representative sample is obtained, the interval is purged a minimum of three times prior to sample collection. The first purge volume is equal to the volume within the discharge tubing reel (about 6.12 gallons) plus the volume within the isolated interval. The next two purges need only remove the volume of the isolated interval. Field properties (pH, temperature, specific conductance, and dissolved oxygen) are monitored and recorded during purging (fig. 16). After at least three purge volumes have been removed and field properties have equilibrated, the ground-water sample is collected within the ground-water sample-collection chamber (fig. 8).

Testing of Hydraulic Properties

The hydraulic response within an isolated interval can be assessed by monitoring head changes in response to the removal or injection of fluids or pressurized air. Commonly, aquifer tests are conducted at the same time as water-quality sample collection. Under a constant pumping rate with a constant interval head, drawdown can be analyzed using the steady-state analytical solution presented by Thiem (Thiem, 1906, Singhal and Gupta, 1999) to provide an estimate of transmissivity. Non-steady-state drawdown under a constant

purge rate may be analyzed by using non-steady-state analytical solutions, including but not limited to Cooper and others (1967) and Hantush (1961), to provide an estimate of transmissivity. A hydraulic response that is characteristic of a low permeability discontinuity is a rapid decrease in hydraulic head at the onset of pumping, and negligible recovery following the cessation of pumping. For example, an isolated interval in well PER566 had a rapid head loss and an erratic pumping rate followed by an abrupt decrease in pumping rate, suggesting dewatering of the interval. The absence of recovery after cessation of pumping indicates this interval contributes a negligible amount of water to the well (fig. 17).

A multistep injection test also may be used to estimate the transmissivity of an isolated zone (fig. 18). The first step of the injection test is conducted at a pressure of 15 psi. Following a step time of at least 10 minutes, additional step increases may be performed by increasing the pressure within the injection tank and holding it constant for the duration of the step. At the end of the final step, the test is ended by closing the down-hole injection valve. Figure 18 shows the response from the three-step injection test with injection rate and hydraulic head at quasi-steady-state conditions. Data can be analyzed using a modification of the Thiem equation (Thiem, 1906; Singhal and Gupta, 1999).

The straddle packer may also be used to deliver a pressurized slug of water into the interval. First, pneumatic pressure is applied to water contained in the injection tank. Pressure generally is held constant at 15 psi. After 15 psi has been reached, the slug of water is directed into the discharge line leading to the isolated interval. The slug is delivered into

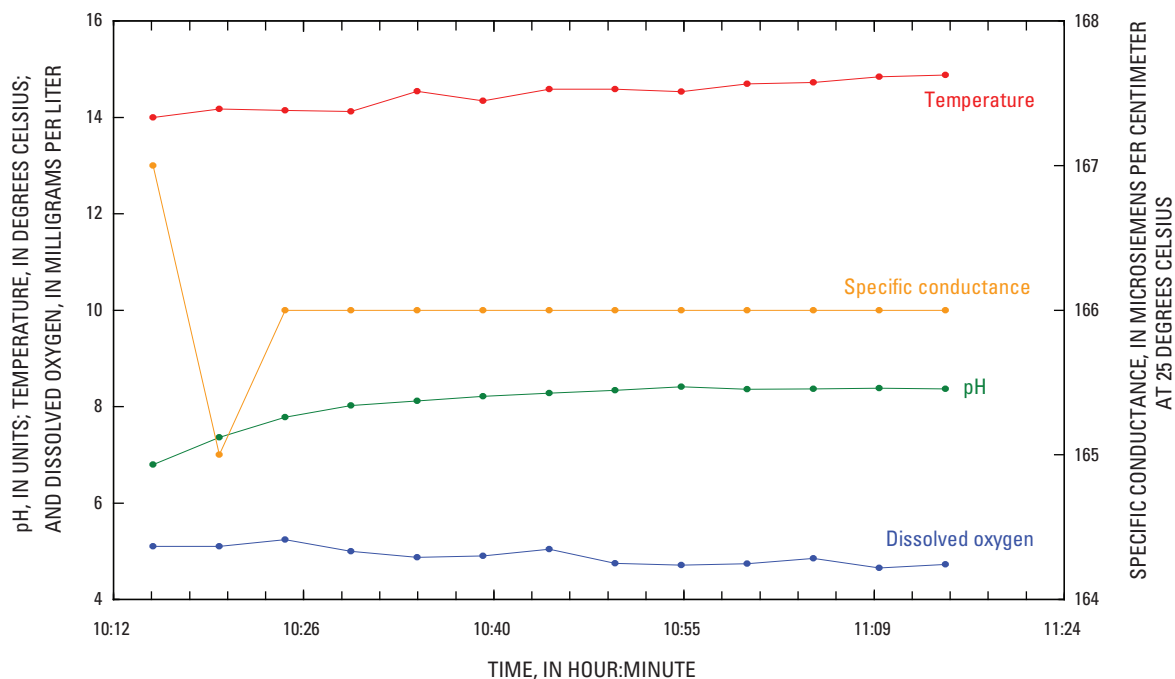


Figure 16. Field water-quality properties during pumping using the AFP6 straddle packer located at 330 feet, well PER569, U.S. Air Force Plant 6, Marietta, Georgia, February 1, 2005. See figure 1 for well location.

the interval with a pneumatically actuated injection valve. Emplacement of the slug can be observed with an in-line flow indicator, and the duration of the slug can be precisely controlled. Analytical solutions provided by Hvorslev (1951),

Cooper and others (1967), Papadopulos and others (1973), and Bredehoeft and Papadopulos (1980) can be used to assess the decreasing hydraulic head (recovery) observed within the interval following the slug injection.

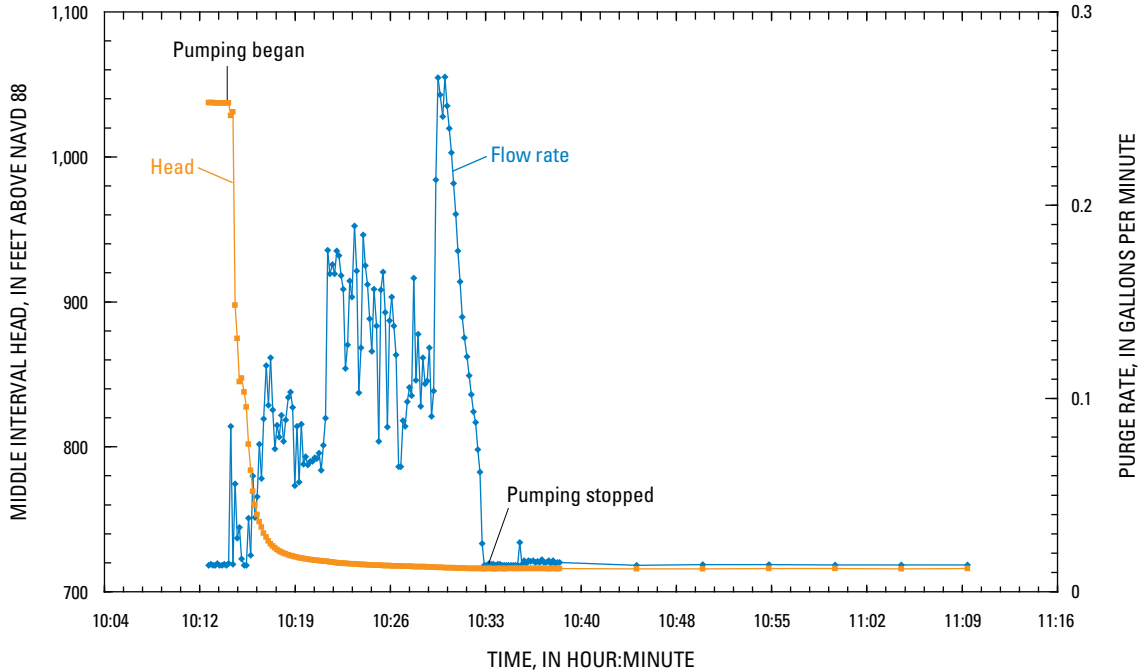


Figure 17. Middle interval response during pumping of low-permeability zone located at 297 feet, well PER566, U.S. Air Force Plant 6, Marietta, Georgia, October 6, 2004. See figure 1 for well location.

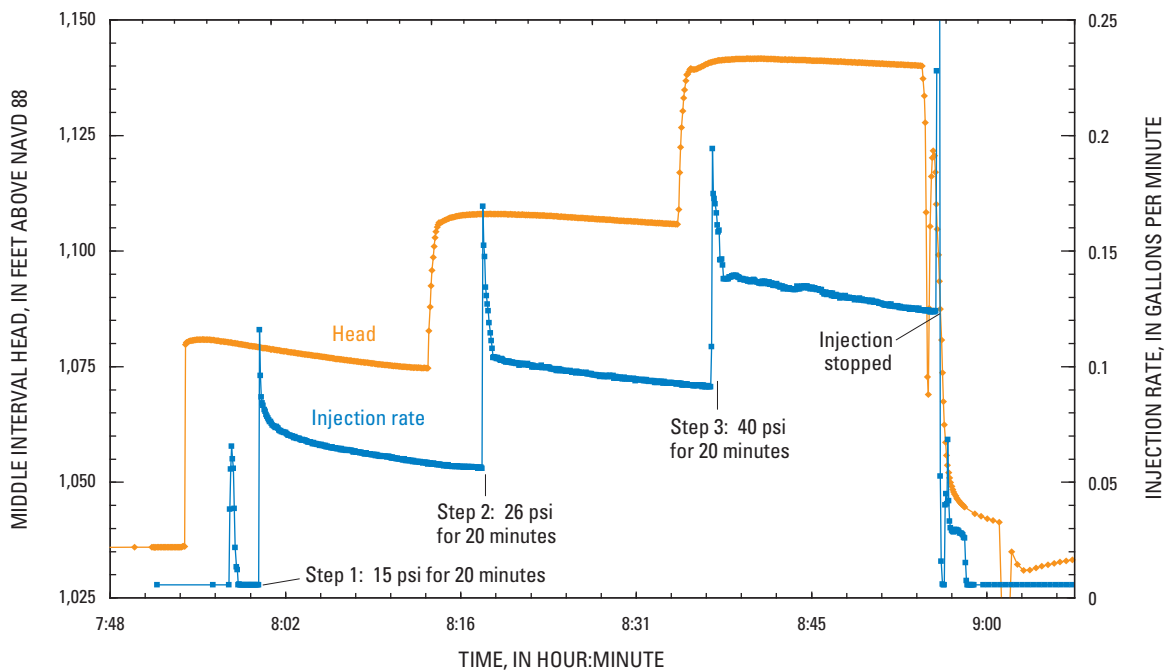


Figure 18. Middle interval response to three-step injection test located at 428 feet, well PER566, U.S. Air Force Plant 6, Marietta, Georgia, October 14, 2004. See figure 1 for well location. [psi, pounds per square inch]

Decontamination of Straddle Packer

The straddle packer is decontaminated while inside the well between sample collections and when removed. Following each sample collection event, deionized water is flushed through the discharge tubing reel and down-hole discharge tubing into the interval being investigated. Typically, if a straddle packer injection test is conducted this serves as the initial deionized water flush. Additionally deionized water is flushed through the up-hole flowmeters and ground-water sample-collection chamber located in the water-quality trailer. Upon removal from the well, the straddle packer is disassembled and washed thoroughly with phosphate-free detergent and deionized water.

Assessment of Straddle-Packer Performance

To assess the performance of the AFP6 straddle packer and the adequacy of operating procedures, comparisons are made for the pressure transducers and the dual-pump sample-collection system. Hydraulic head and water-quality data collected from July 2005 to October 2005 using the straddle packer investigation of well B4MWHH (fig. 1, table 1) are used as a basis for the assessment.

Pressure Sensing System

During straddle-packer use, transducer readings and water-level measurements are recorded during periods when the packers are inflated to the ambient hydrostatic pressure. At the time of measurement, the depth of each transducer

is known, and the true water-column height above each transducer can be calculated using equation 1.

The accuracy of transducer readings can be assessed in real time during straddle packer deployment. Transducer readings can be compared to computed water-column height above the transducer during straddle packer deployment in well B4MWHH (fig. 19). Transducer readings for the middle and lower intervals matched the computed water-column height with a coefficient of determination (R^2) greater than 0.99.

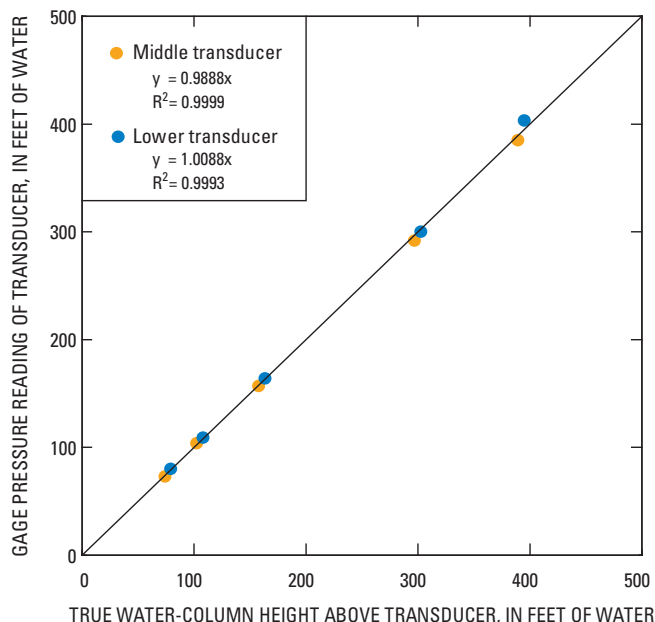


Figure 19. Comparison of transducer readings and computed water-column height above the transducer during straddle-packer deployment, well B4MWHH, U.S. Air Force Plant 6, Marietta, Georgia, July 2006. See figure 1 for well location.

Table 1. Location and construction information for selected test wells at U.S. Air Force Plant 6, Marietta, Georgia.

[USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988; °, degree; ', minute; ", second; do., ditto]

Well identification				Open interval					
Site name	USGS station number	Latitude	Longitude	Altitude of land surface (in feet above NAVD 88)	Date of completion (month/day/year)	Depth of casing (in feet below land surface)	Borehole depth (in feet below land surface)	Diameter (in inches)	Type of casing
B4MWHH	09FF90	33°55'47.00"	84°31'33.00"	1,103.28	1/12/2001	54	600	6	Steel
PER566	09FF76	33°54'51.80"	84°31'43.50"	1,043.06	2/17/2004	80	600	6	do.
PER568	09FF74	33°55'08.80"	84°31'17.40"	1,007.05	3/1/2004	39	407	6	do.
PER569	09FF75	33°55'42.90"	84°32'22.50"	1,134.76	3/26/2004	92	480	6	do.

Dual-Pump System

The straddle packer includes a dual-pump system consisting of a Bennett 1800-8 air-driven piston pump (air-piston) and a Grundfos® Redi-Flo 4® model 5E17 VFD, electric, submersible pump (electric pump). A procedural duplicate was performed to determine the effect of pump selection upon measured VOC concentrations. In the process of lifting water to land surface, pumps have the potential to adversely affect the chemical composition of the water sample. Prior to testing, it was assumed that an air-piston pump provided a more representative ground-water sample than an electric pump. This assumption was based upon the possibility that electric pump impellers could displace dissolved gases during lifting of ground water. A comparison test was performed on an isolated interval at 215 ft in well B4MWHH on July 18, 2005, and August 3, 2005. Following interval purging with the air-piston pump, replicate samples were collected. Immediately after sample collection terminated, the pump was stopped and the electric pump was activated and pumped until water within the hose line and reel was removed (more than 6.12 gallons). Replicate samples were collected using the electric pump. Analytical results for select VOCs are shown in figure 20 and table 2. Little difference was observed between the samples collected with the two pumps during the two sampling events in July and August 2005.

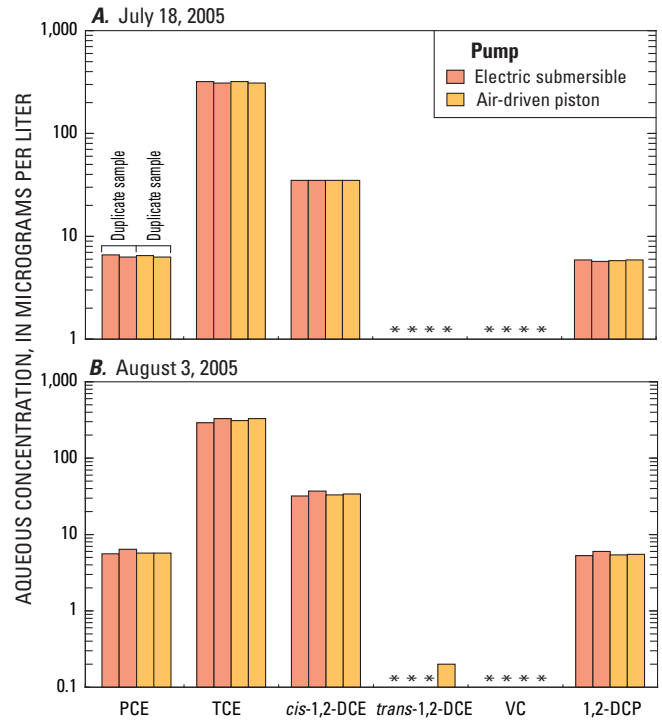


Figure 20. Comparison of analytical results for replicate samples collected using electric submersible and air-driven piston pumps, (A) July 18, 2005, and (B) August 3, 2005, located at 215 feet, well B4MWHH, U.S. Air Force Plant 6, Marietta, Georgia. [* , nondetect]

Table 2. Selected analytes and analyte concentrations detected in ground-water samples collected during a comparison between an air-driven piston pump and an electric submersible pump at well B4MWHH, U.S. Air Force Plant 6, Marietta, Georgia, July 18, 2005, and August 3, 2005.

[LRL, laboratory reporting level; all concentrations and LRLs are in micrograms per liter; E, estimated; ND, nondetect]

Analyte	Air-driven piston pump		Air-driven piston pump (replicate)		Electric submersible pump		Electric submersible pump (replicate)	
	Concentration	LRL ¹	Concentration	LRL ¹	Concentration	LRL ¹	Concentration	LRL ¹
July 18, 2005								
Tetrachloroethylene (PCE)	6.6E	10	6.3E	13	6.5E	10	6.3E	10
Trichloroethylene (TCE)	320	10	310	13	320	10	310	10
cis-1,2-dichloroethylene	35	10	35	13	35	10	35	10
trans-1,2-dichloroethylene	ND	10	ND	13	ND	10	ND	10
1,2-dichloroethylene (total)	35	10	35	13	35	10	35	10
1,1-dichloroethylene	ND	10	ND	13	ND	10	ND	10
Vinyl chloride	ND	10	ND	13	ND	10	ND	10
1,2-dichloropropane (1,2-DCP)	5.9E	10	5.7E	13	5.8E	10	5.9E	10
August 3, 2005								
Tetrachloroethene (PCE)	5.6	10	6.4	1.0	5.7	1.0	5.7	1.0
Trichloroethene (TCE)	290	10	330	10	310	10	330	10
cis-1,2-dichloroethylene	32	1.0	37	1.0	33	1.0	34	1.0
trans-1,2-dichloroethylene	ND	1.0	ND	1.0	ND	1.0	0.2E	1.0
1,2-dichloroethylene (total)	32	1.0	37	1.0	33	1.0	34	1.0
1,1-dichloroethylene	1.4	1.0	1.7	1.0	1.4	1.0	1.4	1.0
Vinyl chloride	ND	1.0	ND	1.0	ND	1.0	ND	1.0
1,2-dichloropropane (1,2-DCP)	5.3	1.0	6.0	1.0	5.4	1.0	5.5	1.0

¹ Due to dilutions at the laboratory, LRLs may vary among samples and analytes

Effect of Tubing Reel on Ground-Water Sample Collection

A test was performed on July 20, 2005, in well B4MWHH to determine if stagnation of water in the tubing reel affects VOC concentrations. Prior to testing, it was assumed that dissolved gases could collect within the tubing reel resulting in falsely inflated VOC concentrations. The test was conducted by isolating the interval surrounding 215 ft in well B4MWHH and collecting replicate samples through the reel using the air-piston pump. Immediately following the initial sample collection, the pump was stopped and the discharge tubing was routed to bypass the tubing reel. Replicate samples were then taken. Analytical results for select VOCs are shown in figure 21 and table 3. As with the pump comparison test, little difference was observed between the samples collected with or without the reel.

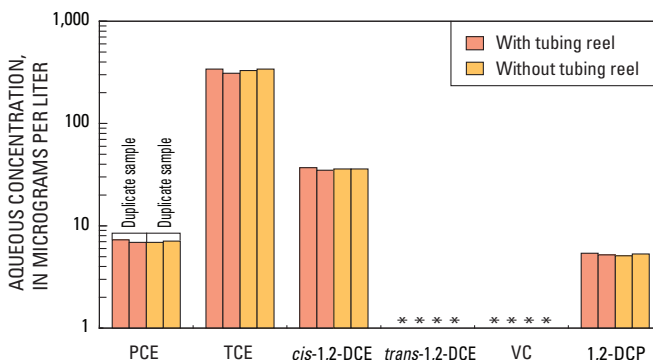


Figure 21. Comparison of analytical results for replicate samples collected using an air-driven piston pump through a tubing reel and bypassing the tubing reel located at 215 feet, well B4MWHH, U.S. Air Force Plant 6, Marietta, Georgia, July 20, 2005. [* , nondetect]

Table 3. Selected analytes and analyte concentrations detected in ground-water samples collected during a comparison between sampling with and without a tubing reel at well B4MWHH, U.S. Air Force Plant 6, Marietta, Georgia, July 20, 2005.

[LRL, laboratory reporting level; all concentrations and LRLs are in micrograms per liter; E, estimated; ND, nondetect]

Analyte	Sample with reel		Sample with reel (replicate)		Sample without reel		Sample without reel (replicate)	
	Concentration	LRL	Concentration	LRL	Concentration	LRL	Concentration	LRL
July 20, 2005								
Tetrachloroethylene (PCE)	7.3E	10	6.9E	10	6.9E	10	7.1E	10
Trichloroethylene (TCE)	340	10	310	10	330	10	340	10
cis-1,2-dichloroethylene	37	10	35	10	36	10	36	10
trans-1,2-dichloroethylene	ND	10	ND	10	ND	10	ND	10
1,2-dichloroethylene (total)	37	10	35	10	36	10	36	10
1,1-dichloroethylene	2.0E	10	1.5E	10	1.8E	10	1.8E	10
Vinyl chloride	ND	10	ND	10	ND	10	ND	10
1,2-dichloropropane (1,2-DCP)	5.4E	10	5.2E	10	5.1E	10	5.3E	10

Sampling Method Comparison

In well B4MWHH, a comparison test for three different sampling methods was undertaken from early September to early October 2005. On July 13, 2005, the AFP6 straddle packer was modified with a 25-ft-extension below the shroud to give a total interval length of 34.2 ft as opposed to the normal interval length of 8.6 ft. Because of several discontinuities between 215 and 247 ft, the interval was lengthened to accommodate a proper seal of the upper and lower packers within the well. On September 6, ground-water replicate samples were collected from the isolated zone of 215 to 249.2 ft using the AFP6 straddle packer operating the air-piston pump. On September 8 after the packers were deflated and the system removed, two samples were collected by using grab samplers deployed at depths of 227 to 233 ft. On the same day, two passive diffusion samplers were positioned within the borehole at 229 ft. The diffusion samplers were retrieved and sampled on October 6 after nearly a month of equilibration.

VOC analytical results from ground-water samples collected using the air-piston pump in the isolated interval, grab samplers, and diffusion samplers are shown in figure 22 and table 4. Concentrations of PCE, TCE, and 1,2-dichloropropane (1,2-DCP) were greatest for the samples collected using the air-piston pump in the packed-off interval. Concentrations of *cis*-1,2-DCE and 1,2-dichloroethylene (total) in samples collected using diffusion samplers were nearly 10 micrograms per liter greater than in samples collected by the straddle packer and grab sample methods. Concentrations of *trans*-1,2-DCE was detected only in the grab samples.

The results of this comparison test show that the AFP6 straddle packer yielded the highest levels of TCE, PCE, and 1,2-DCP. The greater value of *cis*-1,2-DCE and 1,2-dichloroethylene (total) within diffusion samples was unexpected and could be a result of greater equilibrium between aqueous concentrations, temporal changes between early September and early October, and/or accumulation of *cis*-1,2-DCE in the diffusion sampler.

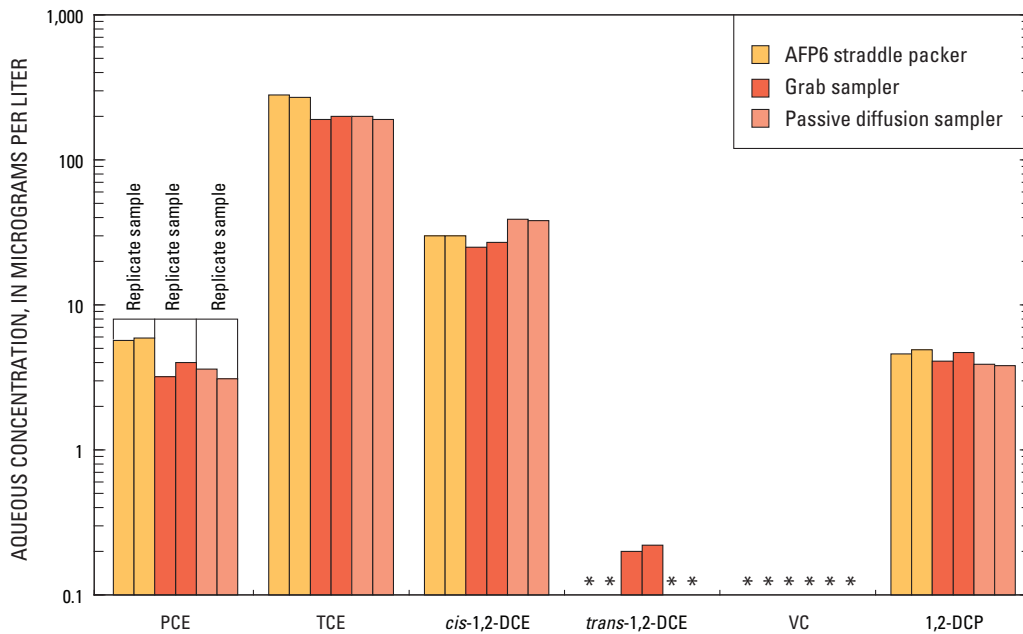


Figure 22. Comparison of analytical results for replicate samples collected using the AFP6 straddle packer, a grab sampler, and a passive diffusion sampler located at 215 feet, well B4MWHH, U.S. Air Force Plant 6, Marietta, Georgia, September–October 2005. [*], nondetect; PCE, tetrachloroethylene; TCE, trichloroethylene; *cis*-1,2-DCE, *cis*-1,2-dichloroethylene; *trans*-1,2-DCE, *trans*-1,2-dichloroethylene; VC, vinyl chloride; 1,2-DCP, 1,2-dichloropropane]

Table 4. Selected analytes and analyte concentrations detected in ground-water samples collected during a comparison among the AFP6 straddle packer, a grab sampler, and a diffusion sampler at well B4MWHH, U.S. Air Force Plant 6, Marietta, Georgia, September 6, 2005, and October 6, 2005.

[LRL, laboratory reporting level; all concentrations and LRLs are in micrograms per liter; E, estimated; ND, nondetect]

Analyte	Straddle packer		Straddle packer (replicate)		Grab sample		Grab sample (replicate)		Diffusion sample		Diffusion sample (replicate)	
	Concentration	LRL ¹	Concentration	LRL ¹	Concentration	LRL ¹	Concentration	LRL ¹	Concentration	LRL ¹	Concentration	LRL ¹
	September 6, 2005						October 6, 2005					
Tetrachloroethylene (PCE)	5.7	1.0	5.9	1.0	3.2	1.0	4.0	1.0	3.6	1.0	3.1	1.0
Trichloroethylene (TCE)	280	5.0	270	5.0	190	6.7	200	6.7	200	4.0	190	5.0
<i>cis</i> -1,2-dichloroethylene	30	1.0	30	1.0	25	1.0	27	1.0	39	1.0	38	1.0
<i>trans</i> -1,2-dichloroethylene	ND	1.0	ND	1.0	0.20E	1.0	0.22E	1.0	ND	1.0	ND	1.0
1,2-dichloroethylene (total)	30	1.0	30	1.0	25	1.0	27	1.0	39	1.0	38	1.0
1,1-dichloroethylene	1.5	1.0	1.4	1.0	0.95E	1.00	1.1	1.0	0.9E	1.0	0.87E	1.0
Vinyl chloride	ND	1.0	ND	1.0	ND	1.0	ND	1.0	ND	1.0	ND	1.0
1,2-dichloropropane (1,2-DCP)	4.6	1.0	4.9	1.0	4.1	1.0	4.7	1.0	3.9	1.0	3.8	1.0

¹ Due to dilutions at the laboratory, LRLs may vary among samples and analytes

Summary

A straddle packer that enables characterization of the vertical distribution of contaminants, head, and hydraulic properties in open-hole wells was developed and tested by the U.S. Geological Survey as part of an ongoing investigation of ground-water contamination in the crystalline bedrock at U.S. Air Force Plant 6 (AFP6) in Marietta, Georgia. The AFP6 straddle packer facilitates ground-water sampling from and hydraulic testing of discrete intervals and delivery of fluids including tracer suites and remedial agents into discrete fractures. The AFP6 straddle packer consists of two inflatable packers, a dual-pump system, a pressure-sensing system, and an aqueous injection system.

Tests were conducted to assess the accuracy of the pressure-sensing system, and samples were collected for water-quality analysis of select volatile organic compounds (VOCs). Pressure-transducer readings matched computed water-column height, with a coefficient of determination (R^2) greater than 0.99. Only slight differences in concentrations were observed between samples collected using the two different types of

sampling pumps during two sampling events in July and August 2005. A test conducted to assess the effect of stagnation of water in the pump tubing reel on VOC concentrations indicated that concentrations were not affected. A comparison test was conducted to assess differences between three water-sampling methods—pumping a packer-isolated interval using an air-piston pump, and collecting samples from the well using a grab sampler and using a passive diffusion sampler. Concentrations of tetrachloroethylene, trichloroethylene, and 1,2-dichloropropane were greatest for the samples collected using the straddle packer in an isolated interval.

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