Characterizing Hydraulic Properties and Ground-Water Chemistry in Fractured-Rock Aquifers: A User's Manual for the Multifunction Bedrock-Aquifer Transportable Testing Tool (BAT^3)

By Allen M. Shapiro

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Volume		
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic inch (in^3)	0.01639	liter (L)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
Flow rate		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
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)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)
Transmissivity		
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8
Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88)

Characterizing Hydraulic Properties and Ground-Water Chemistry in Fractured-Rock Aquifers: A User's Manual for the Multifunction Bedrock-Aquifer Transportable Testing Tool (BAT^3)

By Allen M. Shapiro

Abstract

A borehole testing apparatus has been designed to isolate discrete intervals of a bedrock borehole and conduct hydraulic tests or collect water samples for geochemical analyses. This borehole testing apparatus, referred to as the Multifunction Bedrock-Aquifer Transportable Testing Tool (BAT^3), includes two borehole packers, which when inflated can form a pressure-tight seal against smooth borehole walls; a pump apparatus to withdraw water from between the two packers; a fluid-injection apparatus to inject water between the two packers; pressure transducers to monitor fluid pressure between the two packers, as well as above and below the packers; flowmeters to monitor rates of fluid withdrawal or fluid injection; and data-acquisition equipment to record and store digital records from the pressure transducers and flowmeters. The generic design of this apparatus was originally discussed in United States Patent Number 6,761,062 (Shapiro, 2004). The prototype of the apparatus discussed in this report is designed for boreholes that are approximately 6 inches in diameter and can be used to depths of approximately 300 feet below land surface. The apparatus is designed to fit in five hard plastic boxes that can be shipped by overnight freight carriers. The equipment can be assembled rapidly once it is removed from the shipping boxes, and the length of the test interval (the distance between the two packers) can be adjusted to account for different borehole conditions without reconfiguring the downhole components.

The downhole components of the Multifunction BAT^3 can be lowered in a borehole using steel pipe or a cable; a truck mounted winch or a winch and tripod can be used for this purpose. The equipment used to raise and lower the downhole components of the Multifunction BAT^3 must be supplied on site, along with electrical power, a compressor or cylinders of compressed gas to inflate the packers and operate downhole valves, and the proper length of tubing to connect the packers, the submersible pump, and other downhole components to land surface.

Borehole geophysical logging must be conducted prior to deploying the Multifunction BAT^3 in bedrock boreholes. In particular, it is important to identify the borehole diameter as a function of depth to avoid placing the packers over rough sections of the borehole, where they may be damaged during inflation. In addition, it is advantageous to identify the location of fractures intersecting the borehole wall, for example, using an acoustic televiewer log or a borehole camera.

A knowledge of fracture locations is helpful in designing the length of the test interval and the locations where hydraulic tests and geochemical sampling are to be conducted.

The Multifunction BAT^3 is configured to conduct both fluid-injection and fluid-withdrawal tests. Fluid-injection tests are used to estimate the hydraulic properties of low-permeability fractures intersecting the borehole. The lower limit of the transmissivity that can be estimated using the configuration of the Multifunction BAT^3 described in this report is approximately 10^{-3} square feet per day (ft^2/d). Fluid-withdrawal tests are used to collect water samples for geochemical analyses and estimate the hydraulic properties of high-permeability fractures intersecting the borehole. The Multifunction BAT^3 is configured with a submersible pump that can support pumping rates ranging from approximately 0.05 to 2.5 gallons per minute, and the upper limit of the of the transmissivity that can be estimated is approximately 10^4 ft^2/d. The Multifunction BAT^3 also can be used to measure the ambient hydraulic head of a section of a bedrock borehole, and to conduct single-hole tracer tests by injecting and later withdrawing a tracer solution.

1. Introduction

The spatial distribution of chemical constituents and formation properties that control ground-water flow and chemical transport are often needed in addressing environmental, engineering, geotechnical, and water-supply issues in fractured-rock aquifers (Shapiro, 2002a). Boreholes with long intervals in fractured-rock aquifers are often used for hydrogeologic characterization. Hydraulic and geochemical data collected from such boreholes may not be representative of the ambient conditions in the bedrock because long open boreholes act as high-permeability pathways that connect numerous fractures intersecting the borehole (Shapiro, 2002b).

The flow in the water column of the borehole under ambient and pumped conditions can illustrate the effect that open boreholes can have on the collection of hydraulic data and water samples for geochemical analyses (Shapiro, 2002b). Figure 1 shows the results of a flowmeter survey conducted in a borehole in crystalline rock. Fractures intersecting the borehole, as interpreted from an acoustic televiewer survey, and the transmissivity of discrete intervals of the borehole, as estimated from fluid-injection and fluid-withdrawal tests, are shown along with the results of the flowmeter surveys conducted under ambient and hydraulically stressed conditions in the open borehole. Under ambient conditions in the open borehole, there is downward flow originating at a fracture in the borehole at an elevation of approximately 650 feet (North American Vertical Datum 1988, NAVD 88). In figure 1, water moves down the borehole and exits the borehole at a fracture about 570 ft NAVD 88. The fact that there is downward flow in the borehole implies that there is a difference in the hydraulic heads associated with the two fractures intersecting the borehole. The water level measured in the open borehole, however, is a weighted-average of the hydraulic heads associated with all fractures intersecting the borehole; the water level in the open borehole is biased toward the hydraulic head in those fractures with the highest transmissivity (Shapiro, 2002b). Flow in the open borehole under ambient conditions can affect the distribution of chemical constituents in the ground water. At sites that have contaminated ground water, open boreholes may act to spread contamination to previously uncontaminated sections of the bedrock.

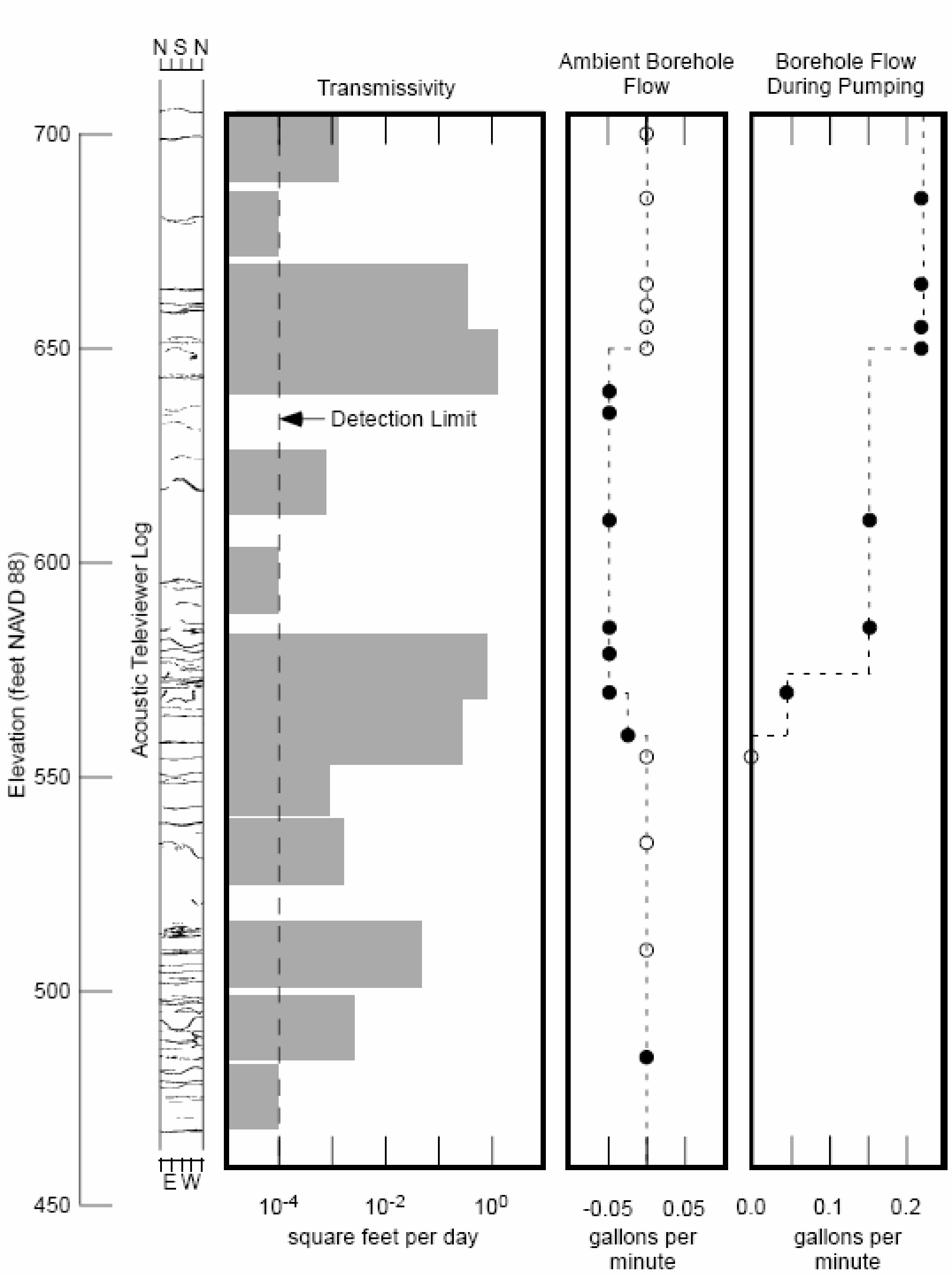

Figure 1. Diagram of a borehole flow meter surveys conducted under ambient and hydraulically stressed conditions in bedrock borehole H1 in the vicinity of Mirror Lake, Grafton County, New Hampshire. Also shown are the interpretation of the acoustic televiewer logging that identifies fractures and their orientation on the borehole walls, and the transmissivity of discrete intervals of the borehole as determined from fluid-injection and fluid-withdrawal.

The lower limit of detection of borehole flow using a flowmeter is approximately 0.01 gallons per minute (gal/min) (Hess, 1986; Paillet, 1998). The absence of measurable borehole flow over the entire length of an open borehole or at specific fractures intersecting a borehole does not necessarily mean that the hydraulic heads of fractures intersecting the borehole are equal. Ambient flow in the borehole at rates below the detection limit of the flowmeter over a long period of time may still greatly affect the distribution of chemical constituents in ground water that flow in the bedrock.

The flowmeter survey conducted under pumped conditions (fig. 1) indicates the ambiguity that will arise in collecting and analyzing water samples for chemical analyses from open boreholes. Data collected from the flowmeter under pumped conditions show that several fractures contribute to the fluid withdrawal from the borehole. The results shown in figure 1 were obtained from pumping at approximately 0.95 gal/min, with the pump intake located in the surface casing above the interval open to the bedrock. The step-wise increase in the flow rate approaching the top of the borehole is the result of fractures contributing to the total volume of water withdrawn from the borehole. Water collected from an open borehole will be drawn preferentially from those fractures with the highest transmissivity. The resulting water sample collected from an open borehole will yield a weighted average of the water chemistry from all fractures intersecting the borehole (Shapiro, 2002b).

One approach to alleviating problems associated with measuring hydraulic properties or collecting ground-water samples in long open boreholes in fractured rock is to drill a borehole with a short interval open to the bedrock, for example, grouting a surface casing in place and leaving a short interval open to the rock below the casing. If multiple intervals at different depths are needed at a given location, this approach requires the drilling of numerous closely spaced boreholes, similar to the installation of nested piezometers in unconsolidated, near-surface deposits. Drilling of nested piezometers in bedrock is often regarded as impractical because of the cost associated with bedrock drilling, and the potential for altering the ground-water chemistry with grout or cement used to secure the surface casing.

To eliminate the effect that long open boreholes have on the collection of hydraulic and geochemical data, borehole packers, also referred to as packers, can be used. Packers are pneumatic or mechanical devices that hydraulically isolate sections of a borehole by forming a seal against the borehole wall (fig. 2). The pneumatic packer shown in figure 3 is constructed using a flexible bladder that can be inflated (with pressurized gas or fluid) once it is placed at the desired location in the borehole. Assigning locations for borehole packers requires a knowledge of borehole conditions such as borehole diameter and the location of fractures, which can be obtained from geophysical logging (Paillet, 1996; Shapiro, 2002b).

Tests using packers to isolate discrete intervals of the borehole can identify variations over the length of the borehole in the hydraulic head, ground-water chemistry, and hydraulic properties of fractures intersecting the borehole. Information from such testing in combination with geophysical logging can be used to identify locations of packers for long-term monitoring of ambient hydraulic and geochemical conditions in the bedrock.

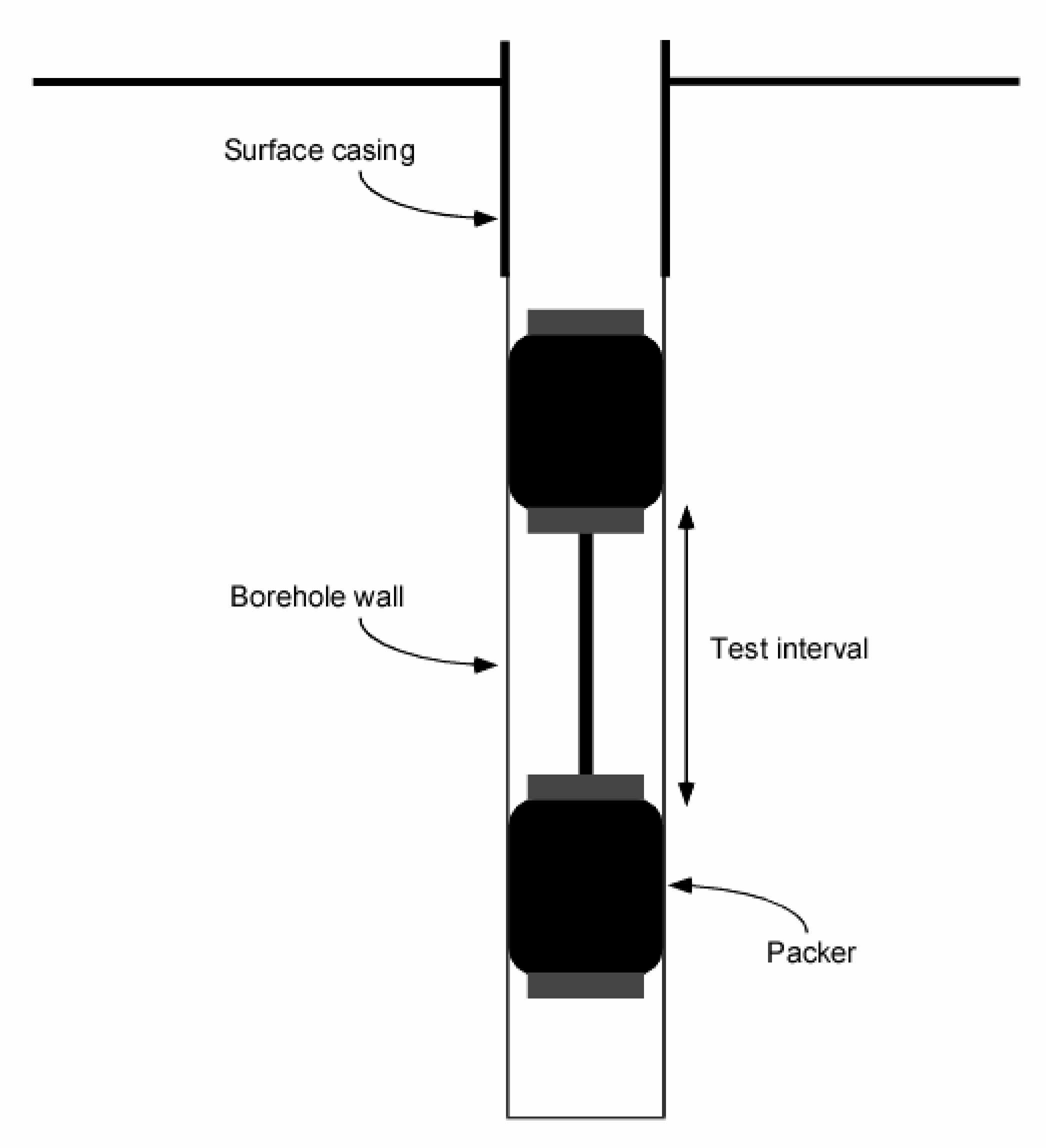

Figure 2. Schematic diagram of borehole packers inflated to form a hydraulically isolated interval in a bedrock borehole.

Hsieh and others (1996) and Johnson and others (2001) used borehole packers to isolate intervals of bedrock boreholes for long-term water-level monitoring. With packers installed, the variation of hydraulic head with depth in the borehole was identified. In addition, the packers used for long-term water-level monitoring isolated intervals of the bedrock and prevented fractures with different water chemistry from communicating with each other through the borehole.

Shapiro and Hsieh (1998) designed packers and downhole equipment for conducting single-hole hydraulic tests in hydraulically isolated intervals of bedrock boreholes by injecting fluid between two borehole packers and measuring the change in the hydraulic head and the fluid-injection rate. Shapiro and Hsieh (1996), Shapiro and others (1999), and Hsieh and Shapiro (1996) showed the application of packers for tracer tests in fractured rock, aquifer tests between multiple boreholes, and geochemical sampling and geophysical logging in bedrock boreholes.

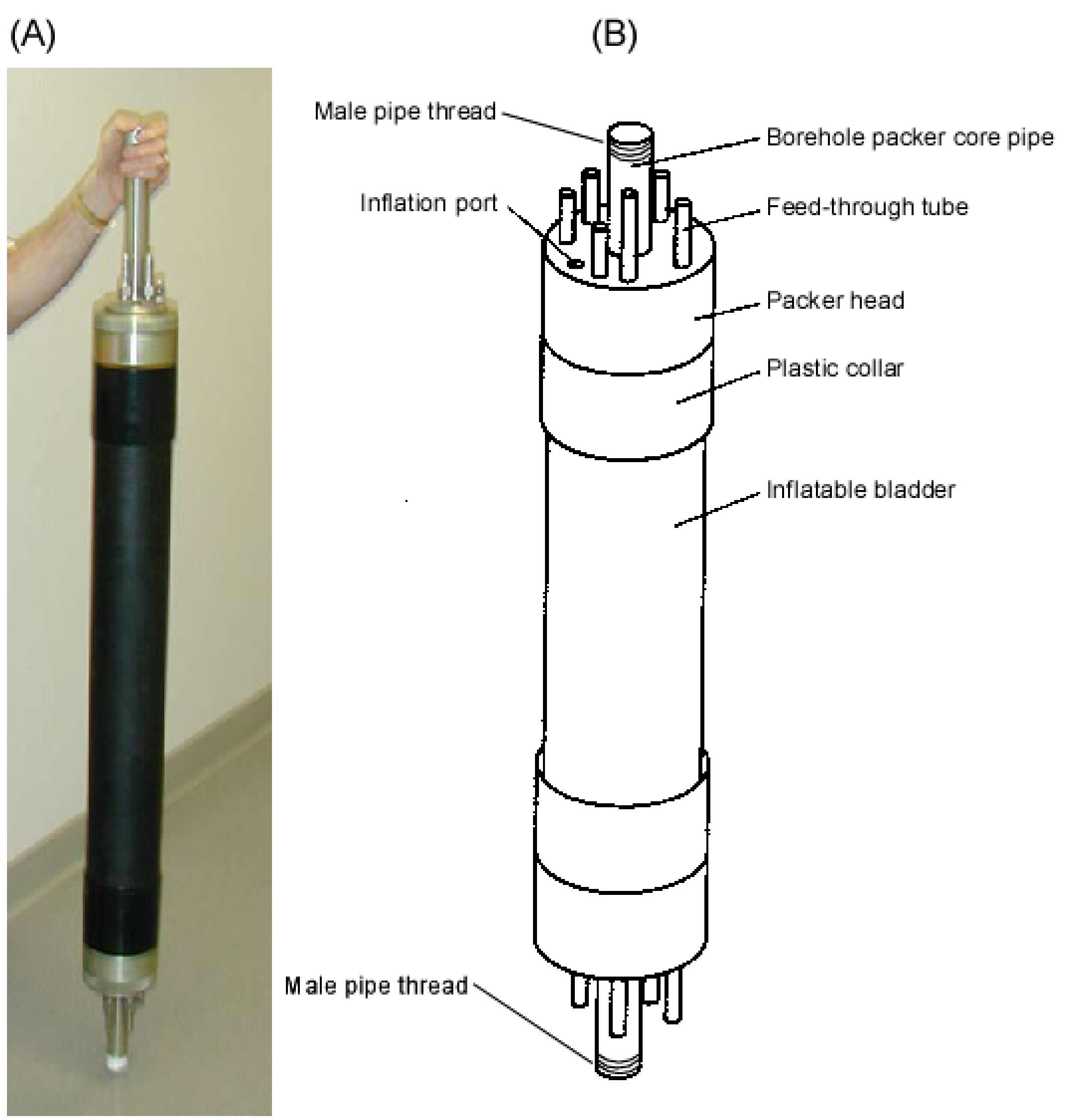

Figure 3. (A) Photograph and (B) schematic diagram of a pneumatic packer.

Depending on the application, packers can be configured with various types of downhole and data-acquisition equipment. Usually, the downhole and data-acquisition equipment for conducting short-term hydraulic tests and collecting water samples for geochemical analyses are constructed for a specific application and borehole conditions at a particular site. The physical dimensions of the downhole equipment and the need for various peripheral components at land surface to control the downhole equipment and data collection make the borehole testing equipment cumbersome and not readily transportable from site to site. Consequently, the use of packers for hydraulic and geochemical characterization in bedrock boreholes is not a common practice. There is a need for borehole testing equipment that can be transported easily and applied over a range of hydraulic conditions in boreholes to estimate the hydraulic properties of fractures and collect water samples for geochemical analyses.

This report describes the design and operation of a transportable borehole packer apparatus and the associated peripheral equipment used for data collection. This equipment is referred to as the Multifunction Bedrock-Aquifer Transportable Testing Tool (BAT^3). The generic design of this apparatus was originally discussed in United States Patent Number 6,761,062 (Shapiro, 2004). The prototype of the apparatus discussed in this report is designed for boreholes that are approximately 6 inches in diameter and can be used to depths of approximately 300 feet below land surface. The borehole equipment is designed to fit into five plastic boxes that can be transported by carriers that offer next-day delivery services. The sizes and weights of the shipping boxes, however, may require special notification for the next-day delivery carrier. The equipment is designed for rapid assembly and can be configured to perform the following operations in a fluid-filled interval of a borehole that is hydraulically isolated by two pneumatic packers: (1) collect water samples for geochemical analysis, (2) identify hydraulic head, (3) conduct a single-hole hydraulic test by withdrawing water, (4) conduct a single-hole hydraulic test by injecting water, and (5) conduct a single-hole tracer test by injecting and later withdrawing a tracer solution. The equipment also can be operated by using only one of the packers, which divides the borehole into two intervals (above and below the operational packer), rather than using both packers to isolate a discrete interval of the borehole.

This report is organized as a reference manual. It is not intended as a document that will be read sequentially at one sitting prior to using the Multifunction BAT^3. For those people who are contemplating using the Multifunction BAT^3 and would like to find out more about its capabilities, it is recommended that they read section "2. Overview of the Borehole Testing Equipment" on page 7, section "7. Information and Equipment Supplied by the User" on page 62, and review the types of tests that can be conducted in section "10. Procedures for Hydraulic Testing and Geochemical Sampling in Boreholes" on page 92. For those people who will be assembling and operating the Multifunction BAT^3, on-site training is usually provided by someone with experience in its assembly and operation. Prior to that training, it is recommended that the user become familiar with the sections "2. Overview of the Borehole Testing Equipment" on page 7, "4. " on page 15, "7. Information and Equipment Supplied by the User" on page 62, and "10. Procedures for Hydraulic Testing and Geochemical Sampling in Boreholes" on page 92. After the on-site training with the Multifunction BAT^3, the user should be able to select sections of this report from the Contents for additional information on the assembly and operation of the downhole components of the equipment, the assembly and operation of the data-acquisition components, the operation of the data-acquisition and data-visualization software, methods of testing using the Multifunction BAT^3, safely deploying and removing the equipment in boreholes, and packing and unpacking the equipment for shipping. Because this document is prepared as a user's manual, there is some degree of redundancy so that the document does not have to be read sequentially, and frequent references are given to sections and page numbers where additional information can be found.

2. Overview of the Borehole Testing Equipment

The generic design of the apparatus described in this report was originally discussed in United States Patent Number 6,761,062 (Shapiro, 2004). The prototype of the apparatus for boreholes that are approximately 6 inches in diameter is the topic of this report. The borehole testing equipment described in this report, which is referred to as the Multifunction Bedrock-Aquifer Transportable Testing Tool (BAT^3), is designed to fit in five shipping boxes. The current configuration of the equipment includes two pneumatic borehole packers to isolate a discrete interval of a bedrock borehole; an electrically powered submersible pump for withdrawing water from between the two packers; downhole valves to control the injection of fluid between the two packers, three pressure transducers for monitoring hydraulic head between the two packers, as well as above and below the packed-off interval; two flowmeters for monitoring fluid injection over a range from 0.00088 to 2.0 gallons per minute (gal/min); a flowmeter to monitor fluid withdrawals during pumping over a range from 0.24 to 10.4 gal/min; data-acquisition equipment to retain a digital record of fluid pressures and flowmeter readings; rechargeable batteries to operate the data-acquisition equipment and flowmeters; a pressure manifold to be connected to either a compressor or cylinders of compressed gas to inflate packers and operate downhole valves; an electric water-level sounder to make manual water-level measurements; a pressure regulator for use on cylinders of compressed gases such as nitrogen; an in-line pressure regulator to regulate the air pressure applied to a fluid reservoir during fluid-injection testing; and a swivel-eye hoisting plug to lower the borehole apparatus in the event that a cable is used to lower the downhole components of the testing equipment.

The borehole equipment has been designed with union ball fittings between the downhole components to allow rapid assembly after opening the shipping boxes. In addition, the downhole equipment is designed such that the test interval (the distance between the packers) can be changed easily to accommodate different borehole conditions; the minimum test interval is approximately 5 ft. The length of the test interval can be increased with 1-inch diameter steel pipe supplied by the user; the appropriate fittings are included in the shipping boxes to attach the steel pipe to the borehole components to increase the length of the test interval. In addition, modular and color-coded connections have been installed on the electrical cables connected to the pressure transducers and flowmeters to allow rapid connection to the data-acquisition equipment.

The downhole equipment supplied in the shipping boxes and discussed in this report is to be used in boreholes that are approximately 6 inches in diameter. The pneumatic packers have an uninflated diameter of 4.75 inches, and upon inflation to the appropriate pressure, the packers will form a hydraulic seal against smooth borehole walls. The choice of borehole locations for the packers and the choice of an appropriate length for the test interval will depend upon borehole conditions. Consequently, testing with the Multifunction BAT^3 should be conducted only after reviewing borehole geophysical logs, including the caliper log to assess borehole roughness, and the interpretation of an acoustic televiewer log or other borehole scanning techniques, such as a borehole video camera, that identify fracture locations and other irregularities in the borehole walls. It is also advantageous to have a borehole flowmeter survey conducted in advance of testing with the Multifunction BAT^3. The flowmeter survey can provide information regarding the location of the most transmissive fractures; this information can be used to design strategies for geochemical sampling and hydraulic testing of discrete intervals of the borehole (Paillet, 1996).

The borehole equipment included in the shipping boxes and discussed in this report is applicable to a depth of approximately 300 ft below the top of the borehole casing. The cables supplied with the electric pump and fluid-pressure transducers for the test interval and below the test interval are each approximately 300 ft in length. The length of the transducer cable used to monitor the fluid pressure above the test interval is only 100 ft in length; this transducer is not connected to the downhole equipment, and it is lowered separately in the borehole to monitor fluid pressure above the top packer. Thus, fluid pressure in boreholes with water levels in excess of 100 ft below the top of the borehole casing will not be able to be measured above the test interval with the pressure transducer that is supplied. Manual measurements of the water level in the borehole with the electric water-level sounder included with this equipment can be conducted in such instances. The downhole equipment can be used in instances where water level in the borehole is in excess of 100 ft below the top of the borehole casing; however, the safe and proper operation of the borehole equipment assumes that testing is conducted in a fluid-filled interval of the borehole.

To deploy and operate the downhole equipment, the user must supply (1) cylinders of compressed gas (such as compressed air, nitrogen, or argon) or an air compressor to inflate packers, operate downhole valves, and, if necessary, apply pressure to a fluid reservoir tank during fluid injection; (2) a winch and tripod or well-servicing truck capable of lowering the borehole equipment; (3) access to 120 volt (V) alternating current (AC) electric power, if the electric pump is to be used to withdraw water from the borehole; (4) a laptop computer with the Windows 2000 or XP operating system to download digital data from the data-acquisition equipment and view the real-time acquisition of the pressure transducer and flowmeter data; (5) the appropriate type and length of 0.25-inch- and 0.5-inch-diameter tubing to be used in the downhole application; (6) the appropriate apparatus and supplies for collecting and preserving water samples, if geochemical sampling is to be conducted; and (7) equipment and supplies needed for cleaning and decontaminating the downhole equipment, if the equipment comes in contact with contaminants in the ground water. It should be noted that access to 120 V AC electric power is absolutely necessary for the operation of the electric pump for fluid-withdrawal testing; however, it is not needed for other types of downhole testing. Nevertheless, access to 120 V AC electric power is advantageous during the other types of downhole testing for the purpose of operating the laptop computer and charging batteries that operate the data-acquisition equipment

The Multifunction BAT^3 uses a Campbell Scientific CR23X Data Logger to monitor pressure transducers and flowmeters and record the digital records from these sensors. To access the data logger from a laptop computer, a license for a single copy of the Campbell Scientific LoggerNet software has been procured. The installation compact disk (CD) is forwarded to the user along with the borehole equipment. At the completion of testing with the borehole equipment described in this report, the user must remove this software from the laptop computer used for data acquisition. A program to operate and monitor the pressure transducers and flowmeters through the Campbell Scientific CR23X Data Logger are forwarded to the user electronically. Instructions for loading the data-acquisition program on the data logger and downloading digital data from the data logger to the lap top computer are included in this report.

To visualize and interpret the pressure transducer and flowmeter data in real-time during testing, software referred to as the BAT^3 Analyzer has been developed by Winston and Shapiro (2007). This software is designed to operate on a computer with a Windows 2000 or XP operating system, and operates in unison with the Campbell Scientific LoggerNet software. The BAT^3 Analyzer can be forwarded to the user electronically. The instructions for loading and operating the BAT^3 Analyzer are given in a separate report (Winston and Shapiro, 2007).

3. Shipping Boxes

The equipment that comprises the Multifunction BAT^3 is shipped in five hard plastic boxes with foam inserts specifically designed to house each piece of equipment. The positions of the equipment within the boxes are shown in figures 4-8. The boxes are designed so that they can be shipped by carriers that offer next-day delivery services. The sizes and weights of the shipping boxes, however, may require special notification of the shipping services for pick-up and delivery.

The boxes should not be exposed to moisture or precipitation while either open or closed. At field sites, the shipping boxes should be closed and covered with a plastic tarpaulin in the event of precipitation. Unpacking the equipment in the boxes should be conducted so as to avoid water entering the boxes.

The downhole components of the Multifunction BAT^3 are contained in Boxes 1 and 2 (fig. 4 and 5). Box 1 contains the pressure transducer apparatus and transducer cables, the top borehole packer, and the submersible pump apparatus and pump cable (fig. 4). Box 1 also contains wrenches for tightening the union ball fittings that connect the downhole components of the Multifunction BAT^3; a spare union ball fitting is also included in Box 1. Box 1 has dimensions of length, width, and height equal to 70, 36 and 16 inches, respectively, and weighs approximately 175 pounds.

Figure 4. Photograph of Shipping Box 1 containing downhole components of the Multifunction BAT^3.

Figure 5. Photograph of Shipping Box 2 containing downhole components of the Multifunction BAT^3.

Figure 6. Photograph of Shipping Box 3 containing equipment used to control the downhole components of the Multifunction BAT^3.

Figure 7. Photograph of Shipping Box 4 containing flowmeters used with the Multifunction BAT^3.

Box 2 contains the bottom borehole packer and the fluid-injection apparatus (fig. 5). Box 2 also contains a pressure regulator that is suitable for tanks of nitrogen or compressed air, and a swivel-eye hoisting plug, which can be used in combination with a cable and winch to raise and lower the equipment in a borehole. The pressure regulator should not be exposed to moisture or precipitation. Box 2 has dimensions of length, width, and height equal to 70, 18 and 16 inches, respectively, and weighs approximately 140 pounds.

Box 3 contains equipment to control the operation of the downhole components of the Multifunction BAT^3 (fig. 6). Included in Box 3 is a pressure manifold used to distribute compressed gas to borehole packers and valves in the downhole equipment, and a pump control box to operate the submersible pump. Box 3 also includes an electric water-level sounder used to measure the depth to water manually in a borehole. The equipment in Box 3 should not be exposed to moisture or precipitation. After unpacking this equipment, it should be located in a covered area that will shield it from moisture or precipitation. Box 3 has dimensions of length, width and height equal to 51, 28, and 22 inches, respectively, and weighs approximately 120 pounds.

Figure 8. Photograph of Shipping Box 5 containing data-acquisition equipment used by the Multifunction BAT^3.

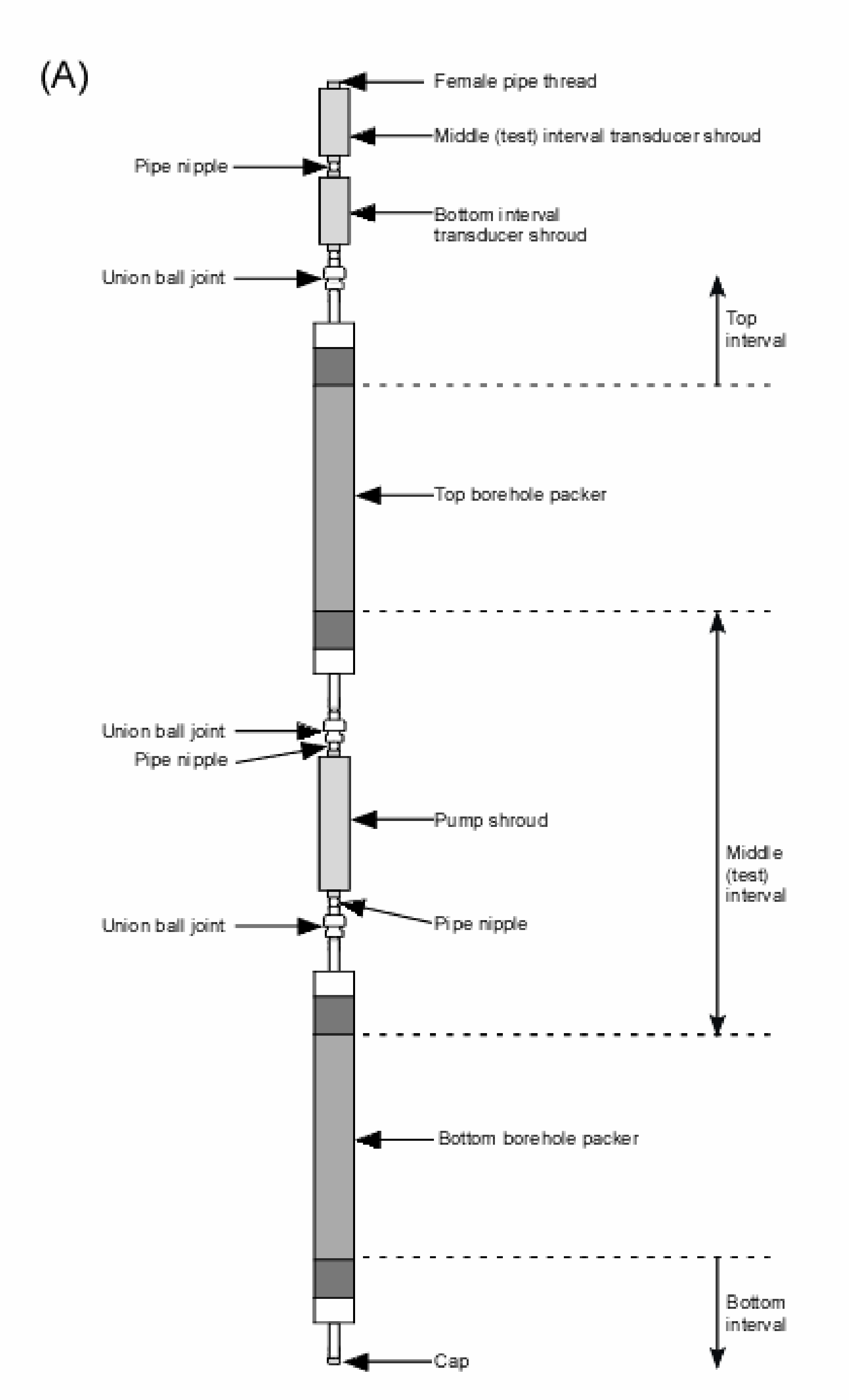

Figure 9. Schematic diagram of the downhole components of the Multifunction BAT^3 configured with (A) a submersible pump, and (B) a submersible pump and fluid-injection apparatus.

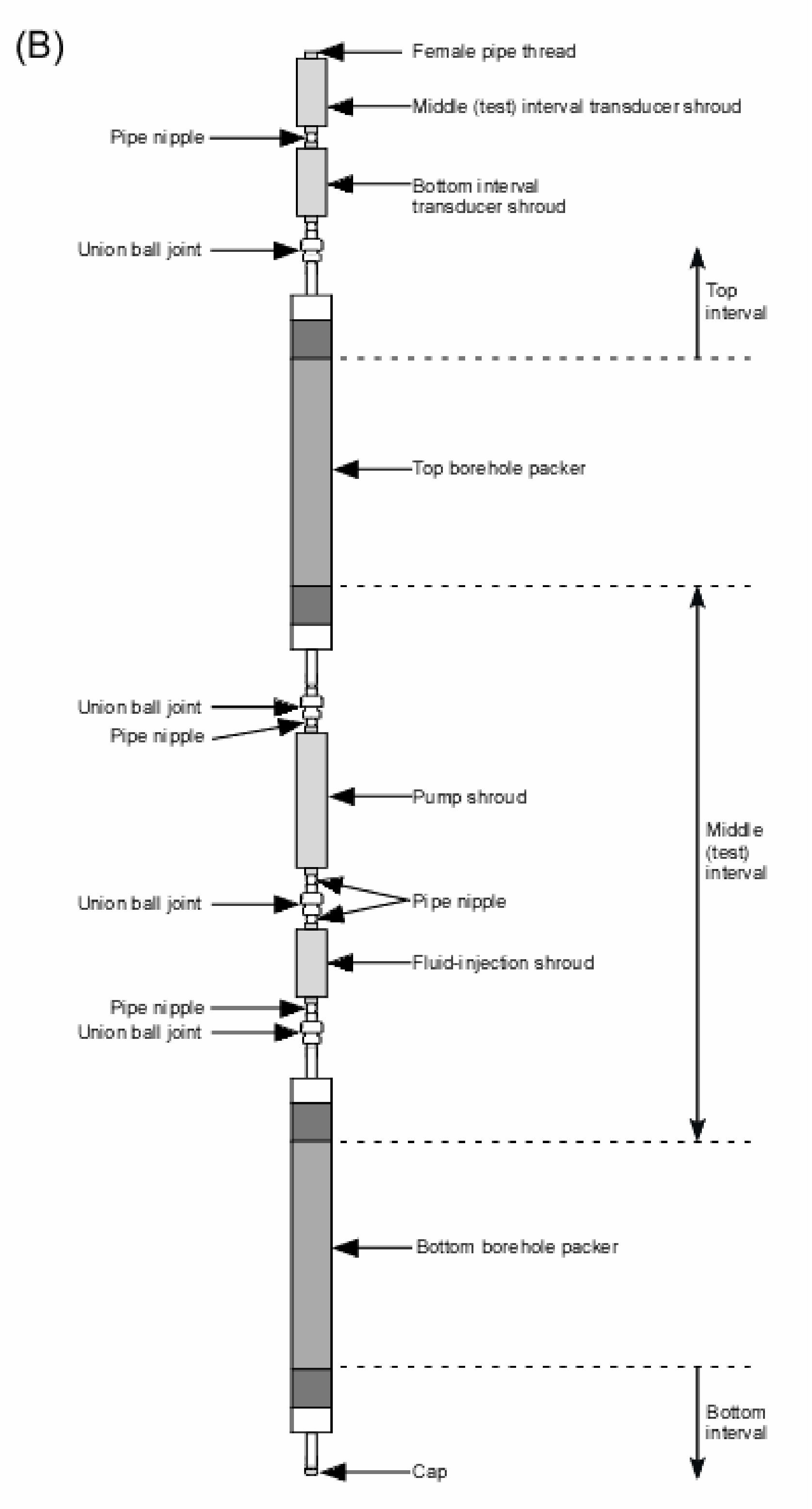

Figure 9. (cont.) Schematic diagram of the downhole components of the Multifunction BAT^3 configured with (A) a submersible pump, and (B) a submersible pump and fluid-injection apparatus.

Boxes 4 and 5 contain equipment used to collect digital data from tests conducted with the Multifunction BAT^3. The equipment in Boxes 4 and 5 should not be exposed to moisture or precipitation. After unpacking Boxes 4 and 5, the equipment should be located in a covered area that will shield it from moisture or precipitation. Box 4 contains two plates that hold flowmeters used to measure fluid-injection and pumping rates (fig. 7). On one of the plates, an in-line pressure regulator is mounted; the in-line pressure regulator can be used to regulate pressure to the water surface in a fluid reservoir tank for fluid-injection testing. The flowmeters and the in-line pressure regulators are mounted on plates so that they are alined properly during testing. Box 4 has dimensions of length, width, and height equal to 37, 27 and 18 inches, respectively, and weighs approximately 95 pounds.

Box 5 contains a pre-wired data-acquisition panel with a Campbell Scientific CR23X Data Logger, a panel of three 12 volt (V) direct current (DC) batteries that operate the data-acquisition equipment, and three adapters to recharge the 12 V DC batteries from a 120 V AC power supply (fig. 8). Box 5 has dimensions of length, width, and height equal to 43, 21 and 14 inches, respectively, and weighs approximately 95 pounds.

The shipping boxes have hasps that secure the lids to the bottom of the boxes. Opening the boxes is performed by rotating the handles of the hasp counterclockwise. The covers on Boxes 1 and 3 lift off the bottom of these boxes; the covers on the other boxes are attached and rotate upward. All five boxes have handles for lifting and moving the boxes, and at least two people will be needed to move each box. Removing equipment from the boxes can be performed by one person, with the exception of the downhole equipment shipped in Boxes 1 and 2, which requires two people. The procedure for removing the downhole equipment from Boxes 1 and 2 is discussed in the section “4.1 Unpacking Downhole Components” on page 16.

4. Downhole Equipment

The downhole equipment of the Multifunction BAT^3 is shipped in Boxes 1 and 2 (fig. 4 and 5) and is schematically shown in figure 9 as it would be assembled for applications. Figure 9 shows two configurations of the downhole equipment, one with only the submersible electric pump between the two packers (fig. 9A), and the second showing both the submersible pump and fluid-injection apparatus between the two packers (fig. 9B). The appropriate configuration will depend on the type of downhole testing to be conducted at a given site. In the section “4.7 Connecting Downhole Components” on page 29, the types of downhole testing are discussed along with the appropriate configuration of the downhole equipment. The downhole equipment includes the following components: (1) pressure transducer apparatus; (2) top packer; (3) pump apparatus; (4) fluid-injection apparatus; and (5) bottom packer. A description of these components is given in this section along with information about unpacking and assembling the components.

Parts of the downhole equipment are housed in shrouds to protect the downhole equipment as they are lowered in a borehole (fig. 10). The shrouds are hollow cylinders with removable end plates. Shrouds are used to house the middle- and bottom-zone transducers that monitor fluid pressure between the two packers and below the bottom packer, respectively, the submersible pump, and the fluid-injection valve. The shrouds for this equipment have different lengths and diameters, but have similar designs. Plates on both ends of the shrouds are secured to the cylinders by screws. The plates have holes to allow electrical cables and tubing to be threaded through them, as well as allowing water movement to the apparatus enclosed in the shroud.

4.1 Unpacking Downhole Components

The fluid-injection shroud in Box 2 (fig. 5) can be removed by one person. Removing the other downhole equipment in Boxes 1 and 2 (fig. 4 and 5) will require two people to avoid injury to the user, or damaging the equipment and the shipping boxes.

4.1.1 Bottom Packer

To remove the bottom packer from Box 2 (fig. 5), one person should be positioned at either end of the packer. The packer should be lifted by its center core pipe, not the tubing that extends through the packer heads (fig. 3). Picking up the packer using the tubes extending through the packer will damage the tubes and may damage the pressure-tight fittings that attach the tubes to the packer heads.

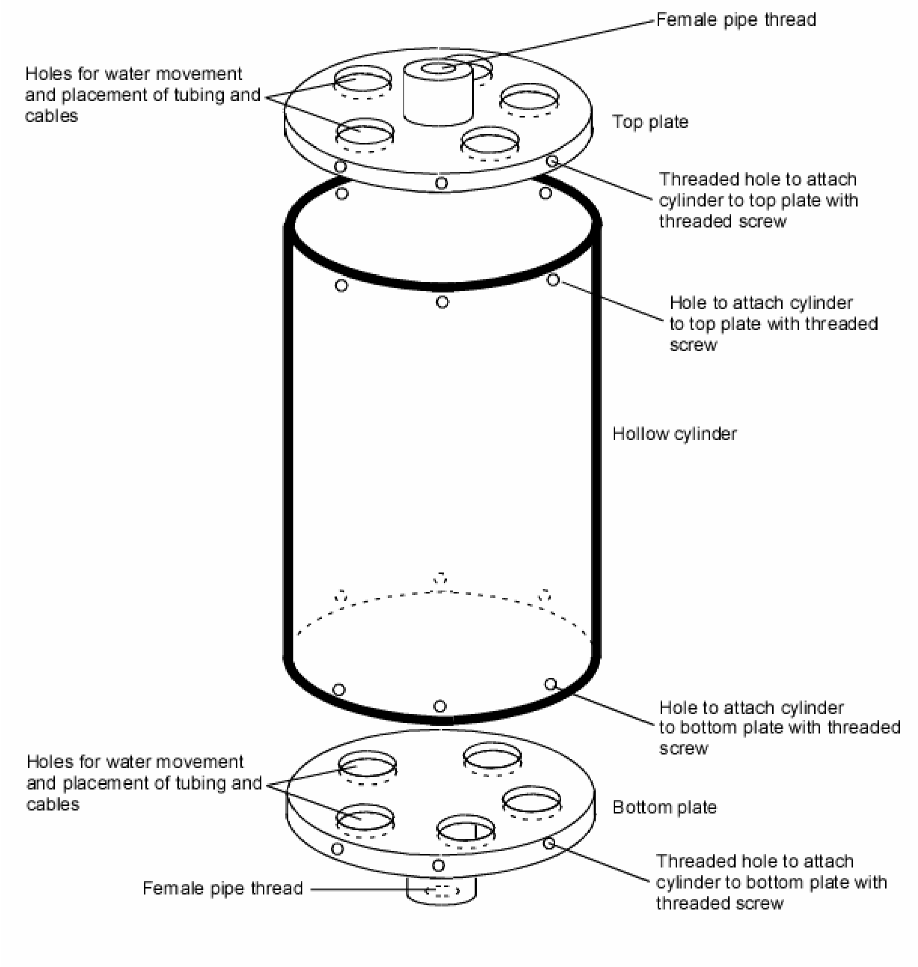

Figure 10. A schematic diagram of a shroud used to protect downhole equipment of the Multifunction BAT^3.

4.1.2 Top Packer, Transducer and Pump Apparatus

The transducer apparatus, the top packer, and the pump apparatus have the pump cable running through them. Figure 11 shows the configuration of these components as they are shipped in Box 1 (fig. 4). Having the pump cable wired through these components permits them to be rapidly assembled once the equipment has been removed from the box. The pump cable is placed in notches cut into the foam insert in Box 1 to avoid being crimped or damaged during shipping. In addition, the middle and bottom transducers are connected to the transducer apparatus, again to permit rapid assembly of the downhole components after they are removed from the shipping box. This equipment should be removed from Box 1 and configured on a clean surface, such as plastic sheeting, outside of the box similarly to the way it is packed in the box (fig. 11). The components are removed from Box 1 in the following order to avoid damaging the transducer and pump cables; two people will be required to lift the downhole equipment from Box 1.

1. The top- or upper-zone transducer is removed first. This transducer is used to monitor fluid pressures above the top packer of the downhole equipment. The top-zone transducer and cable is not connected to the downhole equipment. The top transducer is marked by red-plastic cable ties affixed to the transducer sensor and the uphole electrical connection. The upper-zone transducer cable is coiled and placed in the compartment holding the other transducer cables. The yellow cable at the end of the pressure transducer cable and the connection between the black and yellow cables should not be exposed to moisture or submerged in water.
2. The reel containing the pump cable is then removed and placed outside the box and adjacent to the side of the box with the pressure transducer cables. The electrical connection at the end of the pump cable (on the reel) should not be exposed to moisture or submerged in water.
3. The coils of the transducer cables connected to the two pressure transducer shrouds are then removed from Box 1 and placed near the reel containing the pump cable. These cables are connected to the middle- and bottom-zone transducers. The yellow cables at the end of the pressure transducer cables and the connection between the black and yellow cables should not be exposed to moisture or submerged in water.
4. The pressure transducer shrouds, the top packer, and the pump shroud are then removed from the shipping box. The transducer shrouds, top packer and pump shroud must be removed at the same time, because the pump cable is threaded through these components; these components cannot be removed individually. At least two people will be required to remove these components so as not to damage the pump cable. One person should be positioned on either end of Box 1 (fig. 4). The top packer should be moved only by holding the core pipe of the packer, not the tubing extending through the packer head (fig. 3); lifting the packer by the tubing will damage the tubing and potentially damage the pressure-tight fittings connected to the tubing. The person on the side of the box with the transducer shrouds will need to lift both the top packer and the transducer shrouds. The person on the side of the box with the pump shroud will need to lift both the top packer and the pump shroud. Once these components have been lifted out of the box they should be placed adjacent to the transducer and pump cables similarly to the configuration shown in figure 11.
5. After the pressure transducer apparatus, top packer, and pump apparatus have been placed on the ground adjacent to the shipping box, the transducer shrouds and the pump shroud can be rotated so that the axis of the shrouds alines with the axis of the top packer (fig. 9). These components are then ready to be connected (see section “4.7 Connecting Downhole Components” on page 29).

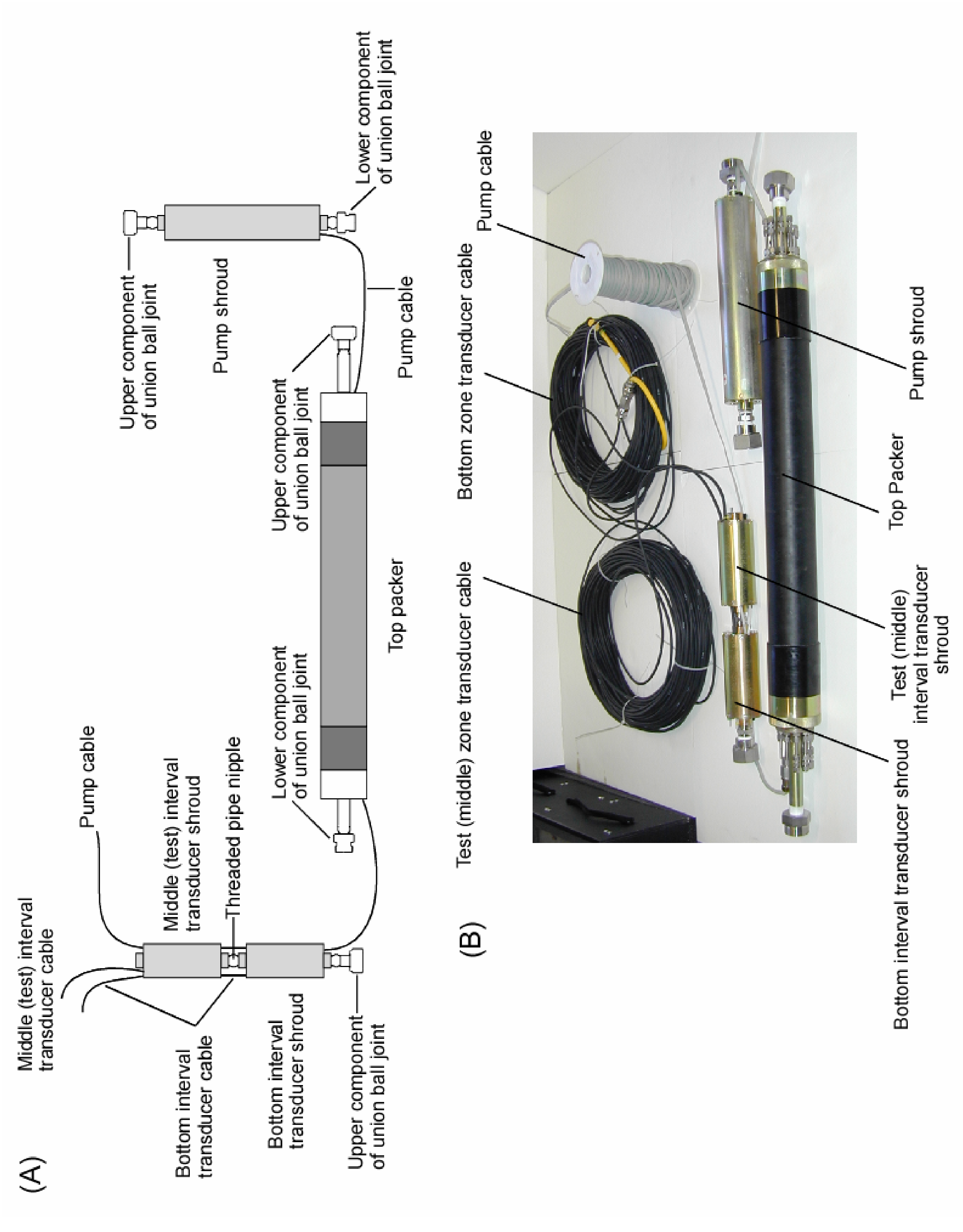

Figure 11. (A) Schematic diagram and (B) photograph of the transducer shrouds, top packer, and pump shroud as they are packed in Shipping Box 1.

4.2 Pressure Transducer Apparatus

Three pressure transducers are included in the Multifunction BAT^3. The pressure transducers monitor fluid pressure in the test- or middle-zone (between the two packers), as well as above and below the top and bottom packers. The transducer that monitors fluid pressure above the top packer is not connected to the downhole equipment. The transducers used to monitor fluid pressures in the test interval and below the bottom borehole packer are housed in transducer shrouds, which are attached above the top packer (fig. 9). Also enclosed in the transducer shrouds are valves that are connected to the transducers, which are used to insure that fluid from the monitored interval is in contact with the transducer sensor. The transducer apparatus of the Multifunction BAT^3 refers to the top transducer, the two transducer shrouds, and the equipment enclosed in those shrouds.

4.2.1 Top-Zone Transducer

The transducer used to monitor fluid pressure above the top packer is not connected to the downhole equipment; it is separate and it should be lowered in the borehole only after the other downhole equipment is placed at the proper location in the borehole. The transducer used to monitor above the top packer is marked with red plastic cable ties at both the transducer sensor and the uphole electrical connection (fig. 12).

Figure 12. Photograph of the pressure transducer used to monitor above the top packer of the Multifunction BAT^3.

The transducer used to monitor fluid pressure above the top packer is a Druck 6-wire PDCR 1830 pressure transducer. The fluid pressure measured at the transducer sensor is proportional to the voltage response from a known excitation voltage; the responses of the pressure transducer are monitored using the data-acquisition equipment of the Multifunction BAT^3. The range of this pressure transducer is from 0 to 50 pounds per square inch absolute pressure (psia), meaning that the transducer measures absolute pressure, such that when the transducer is removed from water, it measures atmospheric pressure. A barometric sensor is connected to the data-acquisition panel of the Multifunction BAT^3 to monitor atmospheric pressure. Data processing is conducted using the BAT^3 Analyzer to subtract the effect of atmospheric pressure from the pressure transducer to arrive at the fluid pressure acting on the transducer sensor (Winston and Shapiro, 2007). The accuracy of this pressure transducer is 0.05 percent (%) of the full range of the transducer, or ± 0.025 pounds per square inch (psi).

Prior to lowering this transducer in the borehole during testing, the red plastic cap covering the transducer sensor should be removed (fig. 12). The uphole end of the transducer cable is fitted with a modular connection (yellow cable) that fits directly into a marked receptacle in the data-acquisition panel of the Multifunction BAT^3. The connection between the yellow and black cables and the electrical connection that attaches to the data-acquisition panel should not be exposed to moisture or submerged in water.

The length of the cable attached to the top transducer is approximately 100 ft. Thus, boreholes with water levels in excess of 100 ft below the top of the borehole casing can not be measured using the pressure transducer that is supplied. Manual measurements of the water level in the borehole using the electric water-level sounder that is included with the Multifunction BAT^3 can be taken in such instances.

Two (2) Druck 6-wire PDCR 1830 pressure transducers with a range from 0 to 50 psia have been calibrated for use with the Multifunction BAT^3. Laboratory calibrations were conducted on these transducers using known pressures applied to the transducer sensor. The calibration relating the height of water above the transducer sensor to the millivolt (mv) response of the transducer (per excitation voltage applied to the transducer) is given in table 1. These calibrations also are supplied in a calibration library that accompanies the BAT^3 Analyzer (Winston and Shapiro, 2007). The serial number of the transducer is printed on the housing of the transducer sensor, and a tag with the serial number is also attached to the uphole end of the transducer cable. The user should check the serial number of the top-zone transducer in choosing the appropriate calibration to convert transducer responses to physically meaningful units. Updates to the laboratory calibrations for these transducers will be included in the calibration library that is supplied with the BAT^3 Analyzer. Field calibration of the top-zone pressure transducer used with the Multifunction BAT^3 is recommended, and the procedure for conducting a field calibration is discussed in the section "9.5 Field Calibration of Pressure Transducers" on page 87.

Pressure transducers with different ranges and cable lengths can be substituted for the transducer currently used to monitor fluid pressure above the top packer. Cable connections and the programming of the data-acquisition equipment, however, may need to be modified to accommodate different transducers.

Table 1. Multiplier and offset from laboratory calibrations of Druck 6-wire PDCR absolute pressure transducers used with the Multifunction BAT[3].

[The calibration of the transducer is given as h = M*mv/V + O, where h is the height of water above the transducer sensor in units of ft, mv/V is the millivolt response of the transducer per excitation voltage, M is the multiplier in units of [ft H_2O][V/mv], O is the offset in units of [ft H_2O], and [ft H_2O] denotes feet of water, psia denotes pounds per square inch absolute pressure.]

Transducer Range, in psia	Serial Number	Multiplier, M, in [ft H_2O][V/mv]	Offset, O, In [ft H_2O]	Calibration Date	Transducer Cable Length, in ft
50	1379785	11.68	-0.70	January 8, 2001	100
50	1379787	11.58	0.23	January 14, 2001	100
100	992056	23.46	-0.06	January 12, 2001	200
100	992057	23.40	-0.41	January 12, 2001	200
200	1379797	50.15	1.20	January 8, 2001	300
200	1379799	50.17	-0.98	January 8, 2001	300
200	1379802	50.12	0.45	March 15, 2001	300
200	1379803	50.14	-0.95	March 16, 2001	300

4.2.2 Middle- and Bottom-Zone Transducers

The middle-zone transducer that monitors fluid pressure between the two packers and the bottom-zone transducer that monitors fluid pressure below the bottom packer are connected to the interval they monitor using tubing and pressure-tight fittings (fig. 13). The tubing that is connected to the transducer sensor extends through the packers to the appropriate interval. The tubing connected to the middle-zone transducer extends through the top packer, and the tubing connected to the bottom-zone transducer extends through both the top and bottom packers.

Because the middle- and bottom-zone pressure transducers are connected to the intervals that they monitor through tubing, air can be trapped in this tubing when the equipment is lowered into a fluid-filled borehole. To remove air that may be trapped in the tubing below the transducer sensor and to insure that fluid is in contact with the transducer sensor, the middle- and bottom-zone transducers are each connected to an air-actuated transducer “bleed” valve (fig. 14). These valves are housed in the transducer shrouds. The “bleed” valves open when an appropriate pressure is applied to a piston housed in the valve. With the valve open, air trapped in the tubing below the transducer sensor can rise out of the tubing and exit through the open valve. Prior to the start of testing, the valves are closed by reducing the pressure applied to the valve pistons. The transducer “bleed” valves are operated with compressed gas administered from land surface, and the valves are connected such that a single tube from a source of compressed gas at land surface actuates both valves (fig. 13).

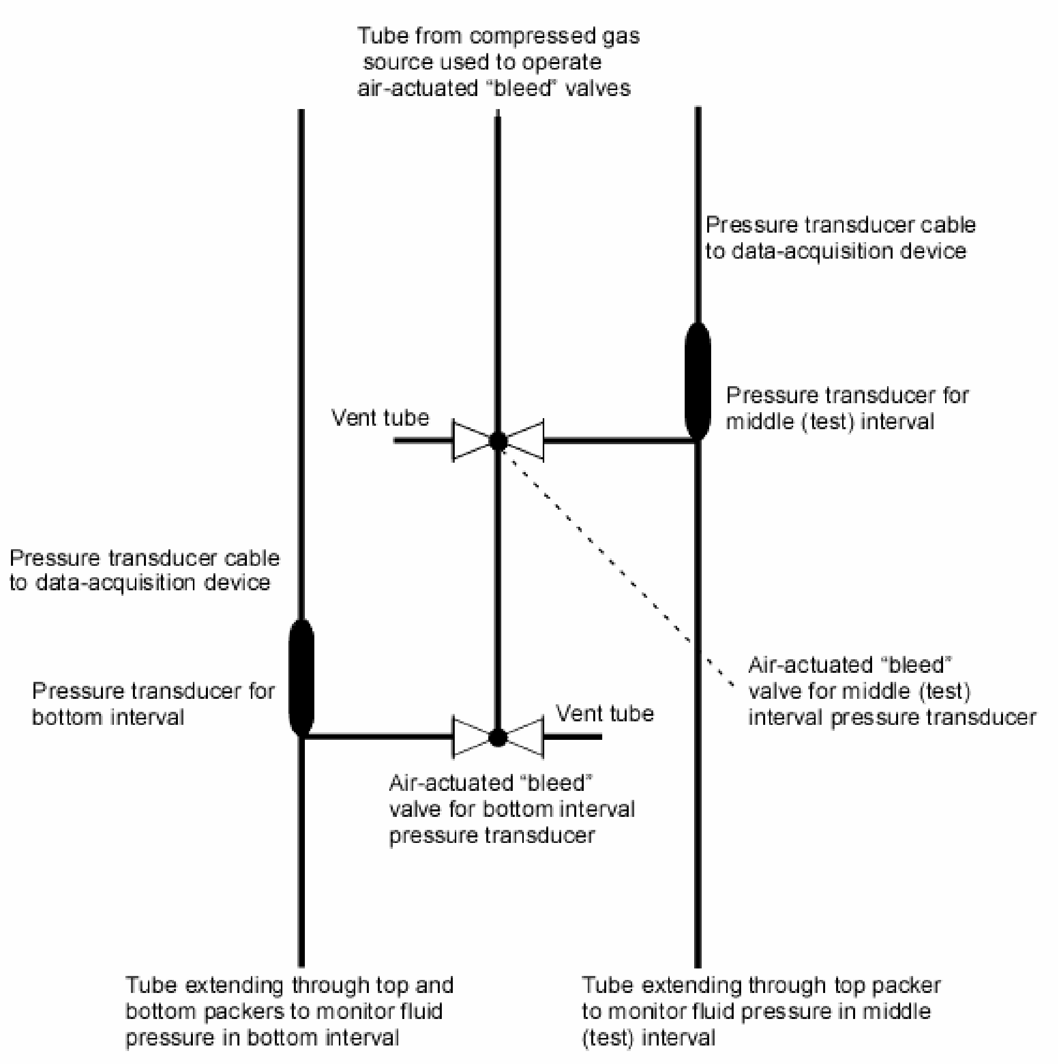

Figure 13. Schematic diagram of the configuration of the middle- and bottom-zone transduers of the Multifunction BAT^3.

The transducer "bleed" valves are Whitey toggle valves (SS-92S4-C-W). The valves have an air actuator, where the valves are closed if a pressure is not applied to the actuator; a pressure of at least 50 psi over the ambient pressure is needed to open the valves. When the valve is submerged in water during testing, the applied pressure to actuate the valve must account for the fluid pressure in the borehole. The pressure needed to open the transducer "bleed" valves can be calculated using the following relation:

$$P_{bleed-valve} = X\ [ft, H_2O] \times \frac{1\,[psi]}{2.31\,[ft, H_2O]} + 50\ [psi] \qquad (1)$$

where $P_{bleed\text{-}valve}$ is the pressure (in psi) that is needed to open the transducer "bleed" valves, when the "bleed" valves are located X ft below the water surface in the borehole, and 1 psi is approximately equal to the pressure of 2.31 ft of water. For example, if the transducer "bleed" valves are located approximately 50 ft below the water level in the borehole, the fluid pressure acting on the transducer "bleed" valves is approximately 22 psi. The pressure applied to the actuator to open the valves under such conditions would need to exceed 72 psi.

The transducer monitoring the middle-zone is marked by a yellow plastic strip at both the transducer sensor and the uphole electrical connection. The transducer monitoring fluid pressure below the bottom packer is marked by a green plastic strip at both the transducer sensor and the uphole electrical connection.

The transducers used to monitor fluid pressure in the middle and bottom zones are Druck 6-wire PDCR 1830 pressure transducers. For these transducers, the fluid pressure measured at the transducer sensor is proportional to the voltage response from a known excitation voltage; the responses of the pressure transducer are monitored using the data-acquisition equipment of the Multifunction BAT^3. The transducers for the middle and bottom zones can be changed depending on the depth at which the Multifunction BAT^3 is to be used in the borehole. Two (2) pressure transducers with a range from 0 to100 psia, and four (4) pressure transducers with a range from 0 to 200 psia are available for use with the Multifunction BAT^3. The 100 psia transducers have approximately 200 ft of cable, limiting their application to about 200 ft below the top of the surface casing. The 200 psia transducers have approximately 300 ft of cable. The 100 psia transducers offer better resolution than the 200 psia transducers. The accuracy of the Druck PDCR 1830 pressure transducers is 0.05 % of the full range of the transducer, or ± 0.05 psi for the 100 psia transducers, and ± 0.1 psi for the 200 psia transducers.

The user should check the serial number of the middle- and bottom-zone transducers in choosing the appropriate calibration to convert transducer responses to physically meaningful quantities. The serial number of the transducer is printed on the housing of the transducer sensor, which is located in the transducer shroud; the serial number is also printed on a tag attached to the uphole end of the transducer cable. Instructions for changing the transducers in the transducer shrouds is given in the section "4.2.3 Replacing Transducers" on page 24.

The uphole end of the transducers cables are fitted with modular connections (yellow cables) that fit directly into marked receptacles on the data-acquisition panel of the Multifunction BAT^3. The connection between the yellow and black cables and the electrical connection that attaches to the data-acquisition panel should not be exposed to moisture or submerged in water.

The pressure transducers that monitor fluid pressure in the middle and bottom zones have been calibrated in laboratory tests using known pressures applied to the transducer sensors. These calibrations are given in table 1, and are supplied in a calibration library that accompanies the BAT^3 Analyzer (Winston and Shapiro, 2007). Updates to the laboratory calibrations for these transducers will be included in the calibration library that is supplied with the BAT^3 Analyzer. Field calibration of the middle- and bottom-zone pressure transducer used with the Multifunction BAT^3 is recommended, and the procedure for conducting the field calibration is discussed in the section "9.5 Field Calibration of Pressure Transducers" on page 87.

Pressure transducers with different ranges and cable lengths can be substituted for the transducers currently used to monitor fluid pressure in the middle and bottom intervals. Cable connections and the programming of the data-acquisition equipment, however, may need to be modified to accommodate different transducers. Replacing the middle and bottom pressure transducers in the transducer shrouds is discussed in the section "4.2.3 Replacing Transducers" on page 24.

4.2.3 Replacing Transducers

Replacing the middle- and bottom-zone transducers may be necessary if the transducers malfunction, or if a transducer with a different range is needed in an application of the equipment. The pressure transducers housed in the transducer shrouds can be replaced by opening the transducer shrouds. The upper transducer shroud houses the middle-zone transducer and the lower transducer shroud houses the bottom-zone transducer. The transducer shrouds are opened by removing the screws that secure the cylinder to the end cap of the shroud (fig. 10). The transducers supplied with the Multifunction BAT^3 have a welded 0.25-inch male National Pipe Thread (NPT) fitting at the transducer sensor. Removing the transducer is performed by using two appropriated size wrenches to unscrew the transducer from the 0.25-inch female NPT fitting that is attached to the transducer "bleed" valve in the transducer shroud (fig. 14). Prior connecting the new transducer, The male NPT threads on the transducer should be wrapped with Teflon tape to insure a pressure tight fitting with the female NPT threads on the fitting attached to the transducer "bleed" valve. The transducer should then be tightened to the fitting on the transducer "bleed" valve using wrenches to insure that the connection is pressure tight.

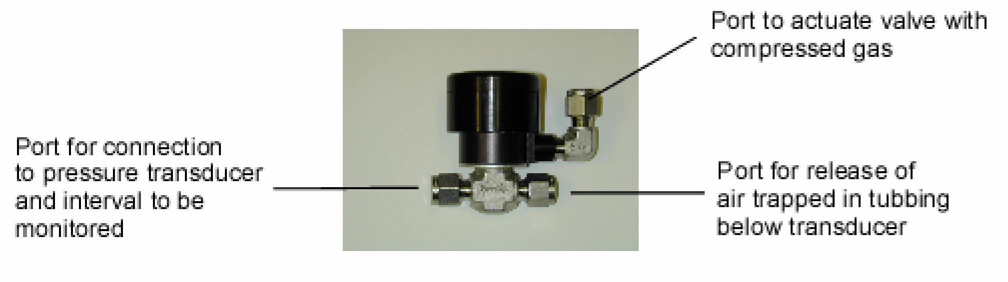

Figure 14. Photograph of the transducer "bleed" valve used to remove trapped air from the tubing extending from the transducer sensor to the monitored interval.

4.2.4 Replacing Transducer "Bleed" Valves

Replacing the transducer "bleed" valves may be necessary if the valves malfunction. The valves housed in the transducer shrouds can be replaced by opening the transducer shroud. The transducer shroud is opened by removing the screws that secure the cylinder to the end cap of the shroud (fig. 10). The transducer "bleed" valves attached to the middle- and bottom-zone transducers are shown in figure 14. The valves used in this design of the Multifunction BAT^3 are Whitey toggle valves (SS-92S4-C-W). The actuator on these valves has 0.125-inch female NPT fitting which is connected to tubing using Swagelok pressure-tight fittings, and the transducer is connected to the "bleed" valve using 0.25-inch Swagelok fittings. The transducer "bleed" valves are removed by using appropriate size wrenches to unscrew the Swagelok and NPT fittings and then reattaching the new air-actuated value in the same location. Instructions for tightening Swagelok fittings are provided by distributors of Swagelok fittings. The male end of NPT fittings should be wrapped with Teflon tape and NPT fittings should be wrench-tight to insure a pressure-tight seal.

4.3 Top Packer

The top packer in the borehole testing equipment is a Roctest YEP-4.75 pneumatic packer. The basic design of the Roctest packer has been altered to meet specifications associated with the applications described in this report. The uninflated diameter of this packer is approximately 4.75 inches. Upon inflation with an appropriate pressure, the packers can seal boreholes with smooth walls of approximately 6 inches in diameter. Additional information about inflating packers for conducting tests in boreholes is given in the sections “9.7 Inflating Packers to Initiate a Test” on page 89 and “9.8 Deflating Packers to End a Test” on page 91.

The packer is inflated using compressed gas administered from land surface through a pressure-tight fitting at the packer head (fig. 3). The top packer has three (3) 0.5-inch-diameter stainless-steel tubes and four (4) 0.25-inch-diameter stainless-steel tubes that extend through the packer. The tubes are designed with Swagelok pressure-tight fittings to prevent hydraulic connection through the packer. The functions of the tubes that extend through the top packer are given in table 2.

The top and bottom packers of the Multifunction BAT^3 are inflated individually from a compressed gas source at land surface. Consequently, testing in bedrock boreholes using the Multifunction BAT^3 can be conducted by inflating one of the packers to divide the borehole into two intervals (above and below the operational packer), or inflating both packers to isolate a discrete interval.

Table 2. The function of the tubing extending through the top packer of the Multifunction BAT^3.

Tubing Diameter in inches	Function
0.25	Monitor fluid pressure in test interval
0.25	Monitor fluid pressure below bottom packer
0.25	Supply pressurized gas to inflation port on bottom packer
0.25	Supply pressurized gas to air-actuator on fluid-injection valve
0.50	Houses pump cable
0.50	Fluid discharge from pump in test interval
0.50	Supply water from fluid reservoir tank at land surface to fluid-injection valve in test interval

4.4 Pump Apparatus

The pump apparatus includes a Grundfos Redi-Flo2 pump system with a Grundfos MP1 pump housed inside the pump shroud (fig. 15). The electrical cable from the pump in the pump shroud is routed through the top packer and transducer shrouds and extends to land surface where it is connected to the Grundfos power converter (fig. 16), which is operated using a 120 V AC electrical power source. The pump is stabilized in the pump shroud by a fitting that connects the pump to the top plate of the pump shroud (fig. 15). The fitting that connects the pump to the top plate of the pump shroud also acts to route fluid through one of the 0.5-inch-diameter tubes in the top packer. Routing the fluid from the pump outlet through one of the stainless-steel tubes in the top packer is advantageous as these tubes can be cleaned and replaced, if necessary.

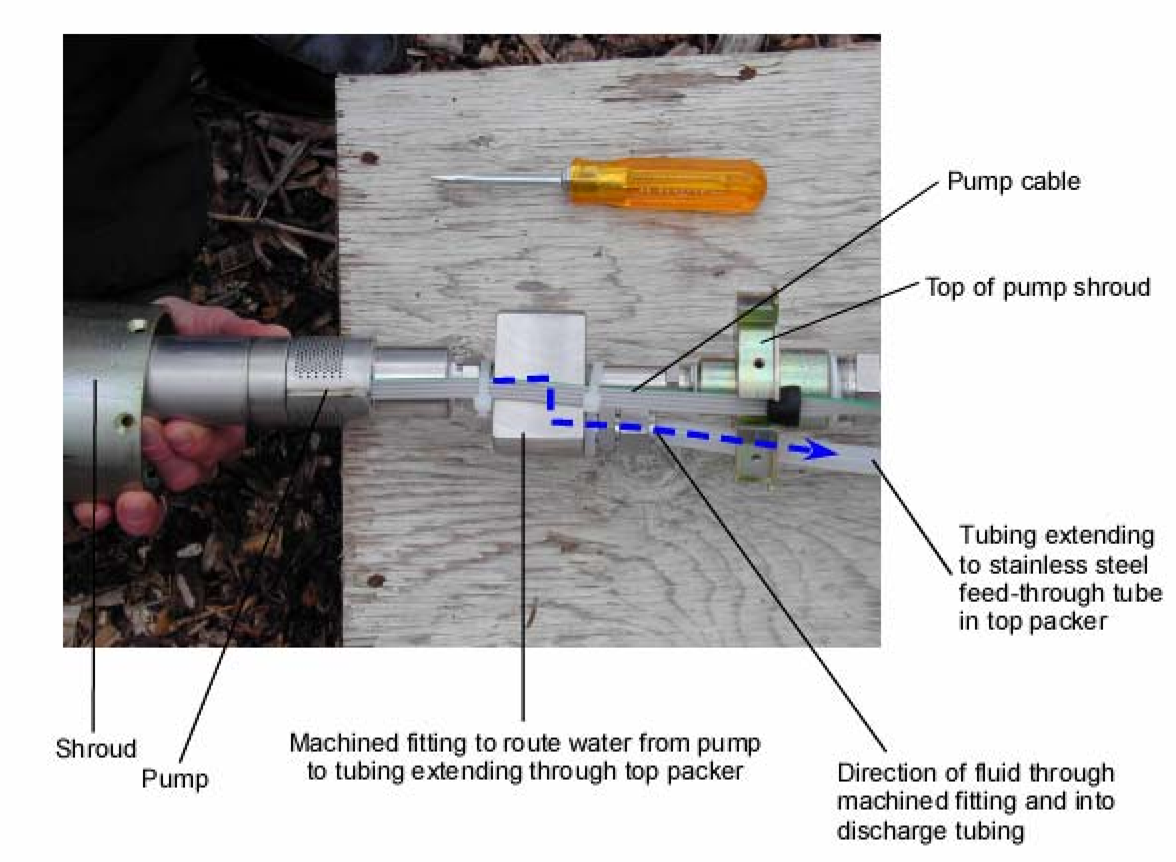

Figure 15. Photograph of the Grundfos MP1 pump in the pump shroud of the Multifunction BAT^3.

The Grundfos Redi-Flo2 pump system is capable of pumping at approximately 9 gallons per minute against a head of approximately 25 feet through 0.5-inch-diameter tubing. Lower pumping rates are achieved for pumping against greater heads. The pump has a diameter of 1.81 inches and is 11.3 inches long. The current configuration of the pump has approximately 300 ft of pump cable. The length of the cable limits the depth at which the borehole apparatus can be used.

Figure 16. Photograph of the Grundfos power converter used to operate the Grundfos MP1 pump.

The 0.5-inch-diameter tubing used to route water from the pump to land surface can reduce the maximum pumping rate that the Grundfos Redi-Flo2 pump system can achieve, because of the resistance the 0.5-inch-diameter tubing offers to flow. The maximum pumping rate will depend on the length of the 0.5-inch-diameter tubing and the height of the water in the borehole above the pump. In general, a pumping rate of approximately 2.5 gal/min can be achieved with approximately 300 ft of 0.5-inch-diameter tubing. Pumping rates greater than 2.5 gal/min may be needed to produce a significant hydraulic stress to estimate hydraulic properties of very transmissive fractures.

4.5 Fluid-Injection Apparatus

The fluid-injection apparatus between the top and bottom packers is used to inject fluid from a fluid reservoir tank at land surface. The fluid-injection apparatus can be used to inject a tracer solution during a tracer test, or to test the hydraulic properties of the test interval by injecting fluid in the test interval while measuring the flow rate and change in fluid pressure in the test interval.

The fluid-injection apparatus consists of a shroud that contains an air-actuated valve (fig. 17). Two stainless-steel tubes connected to the air-actuated valve extend from the shroud and connect to tubing that extend through the top packer. The 0.25-inch-diameter stainless-steel tube extending from the top of the fluid-injection shroud is connected to a source of compressed gas at land surface that is used to actuate a piston in the valve. The valve opens when an appropriate pressure is applied to the piston in the valve. With the valve open, water from a fluid reservoir tank at land surface is injected into the test interval through 0.5-inch-diameter tubing that extends from the fluid reservoir tank through the top packer and out of the fluid-injection valve in the test interval. Reducing the pressure applied to the air actuator of the fluid-injection valve closes the valve and stops fluid injection from the fluid reservoir tank.

Figure 17. Photograph of the air-actuated fluid-injection valve used in the Multifunction BAT^3.

The fluid-injection valve used in the fluid-injection shroud is a Nupro bellows valve (SS-8BK-1C). The valve has 0.5-inch Swagelok fittings for the tube extending from the fluid reservoir tank at land surface. The air actuator on this valve has 0.125-inch female NPT fitting, which is connected to 0.25-inch-diameter tubing using 0.25-inch Swagelok fittings.

The fluid-injection valve is closed if air pressure is not applied to the actuator. A pressure of at least 80 psi over the ambient pressure is needed to open the valve fully. When the valve is submerged in water during testing, the applied pressure to actuate the valve must account for the fluid pressure in the borehole. The pressure needed to open the fluid-injection valve can be calculated using the following relation:

$$P_{injection-valve} = X\ [ft, H_2O] \times \frac{1\,[psi]}{2.31\,[ft, H_2O]} + 80\ [psi] \qquad (2)$$

where $P_{injection\text{-}valve}$ is the pressure (in psi) that is needed to open the fluid-injection valve, when the valve is located X ft below the water surface in the borehole, and 1 psi is approximately 2.31 ft of water. For example, if the fluid-injection valve is located approximately 50 ft below the water level in the borehole, the fluid pressure acting on the valve is approximately 22 psi. The pressure applied to the actuator to open the valve under such conditions would need to exceed 102 psi.

4.6 Bottom Packer

The bottom packer in the borehole testing equipment is a Roctest YEP-4.75 pneumatic packer. The basic design of the Roctest packer has been altered to meet specifications associated with the Multifunction BAT^3. The packer is inflated through a pressure-tight fitting at the packer head (fig. 3) using compressed gas administered from land surface. The bottom packer has two (2) 0.25-inch-diameter stainless-steel tubes that extend through the packer and allow access below the packer. The tubes are fitted with Swagelok pressure-tight fittings to prevent hydraulic connection through the packer. The functions of the tubes that extend through the bottom packer are given in table 3. Additional information about inflating the bottom packer for conducting tests in boreholes is given in the sections “9.7 Inflating Packers to Initiate a Test” on page 89 and “9.8 Deflating Packers to End a Test” on page 91.

Table 3. The function of the tubing extending through the bottom packer of the Multifunction BAT^3.

Tubing Diameter in inches	Function
0.25	Monitor fluid pressure below the bottom packer
0.25	Not used, tube is capped at both ends with pressure-tight fittings

4.7 Connecting Downhole Components

The downhole components for borehole testing are connected using union ball fittings (fig. 18). This type of fitting allows components to be connected together without rotating the components; rotating the nut on the union fitting connects two borehole components together. Using this type of fitting allows the pump and transducer cables to be fed through the downhole components of the Multifunction BAT^3 during shipping, and reduces the time needed to assemble the equipment.

Two wrenches are included with the Multifunction BAT^3 to tighten the union ball fittings (fig. 19). The box ends of the 2.5-inch and 2.375-inch wrenches are used to tighten the nuts on the union ball fittings. These wrenches are shipped in Box 1 (fig. 4).

The configuration of downhole components of the Multifunction BAT^3 is shown in figure 9. To assemble the downhole components of the Multifunction BAT^3, the transducer apparatus, top packer and pump apparatus are aligned, and the union ball fittings are tightened between these components. Prior to tightening the union ball fittings, the pump cable extending from the Grundfos MP1 pump in the pump shroud should be alined so that it forms a straight line from the pump shroud through the top packer and the transducer shrouds to avoid crimping and damaging the pump cable.

The flat pump cable from the Grundfos MP1 pump is then pulled from above the top packer to remove the slack from the cable below the top packer. The tube that extends through the top packer that houses the pump cable has fittings at the ends of the tube. These fittings are then tightened to form a water-tight seal around the pump cable. These fittings are Crouse-Hinds connectors with a specially molded grommet for the flat pump cable of the Grundfos MP1 pump (fig. 20).

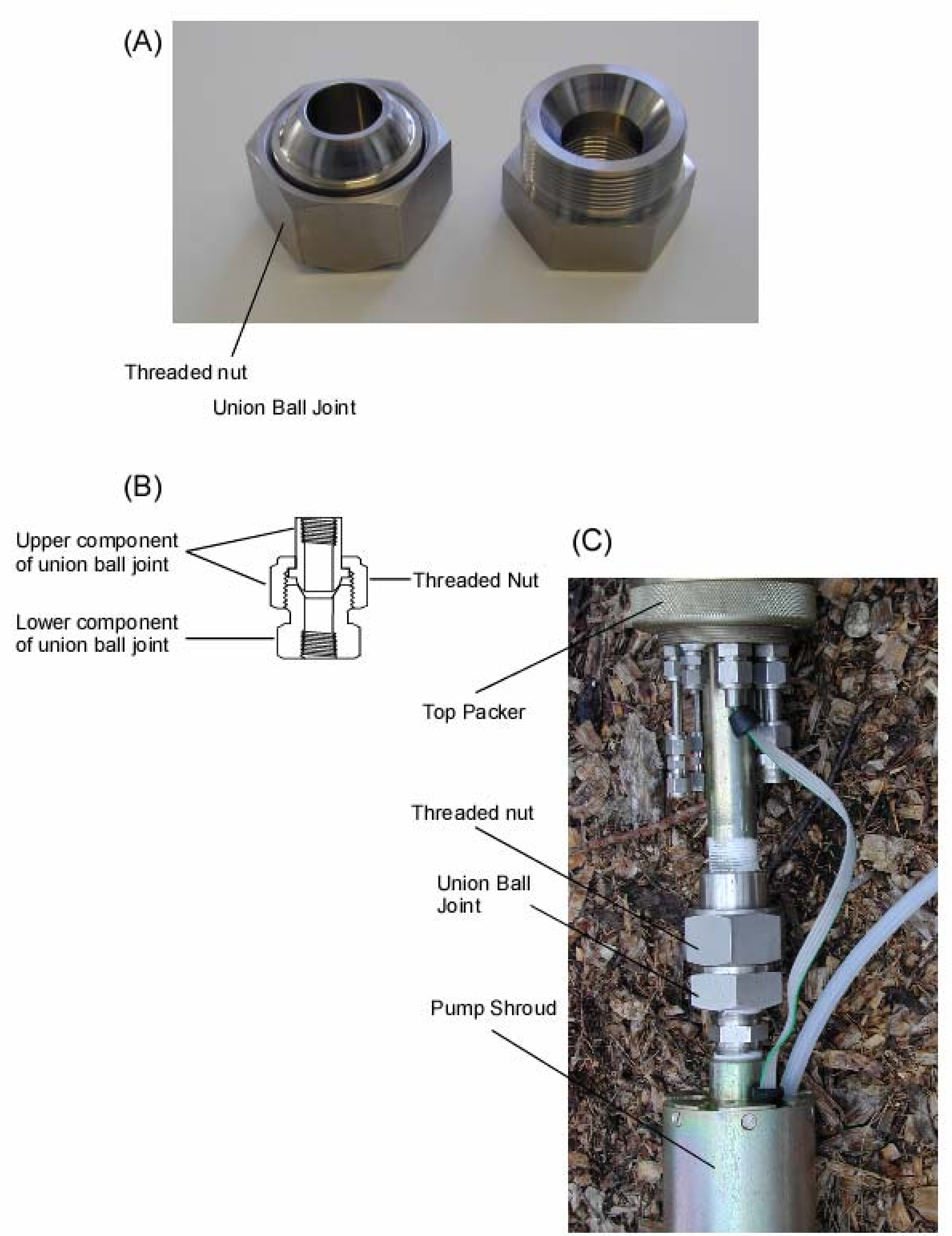

Figure 18. (A) Photograph of the two parts of a union ball fitting, (B) a schematic diagram of a union ball fitting, and (C) a photograph of a union ball fitting connecting the top packer to the pump shroud.

Figure 19. Photograph of wrenches used to tighten the nut on the union ball fitting when connecting downhole components of the Multifunction BAT^3.

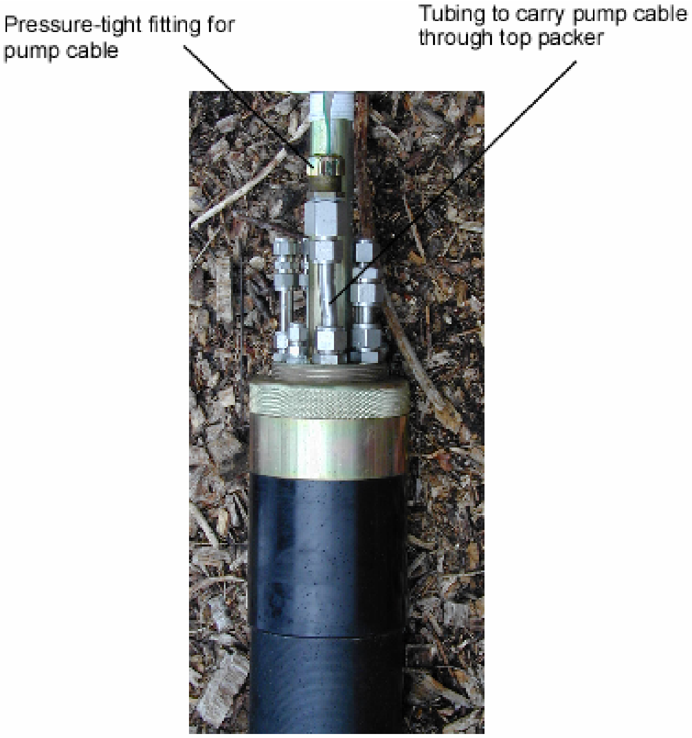

Figure 20. Photograph of the Couse-Hinds connector with a grommet that forms a pressure-tight connection through the top packer for the flat pump cable of the Grundfos MP1 pump.

The pump cable should also be pulled through the transducer shrouds to eliminate any excess pump cable between the top packer and the transducer shrouds. Rubber grommets on the pump cable should be repositioned at the holes on the top and bottom plates of the transducer shrouds (fig. 21). These grommets protect the pump cable from rubbing on the metal shroud and being damaged. In addition, the pump cable should be secured to the center pipe of the apparatus between the pump shroud and the bottom of the top packer, and between the bottom of the transducer shrouds and the top of the top packer. Securing the pump cable to the apparatus reduces the potential for damage to the pump cable as the equipment is lowered in the borehole. Plastic cable ties should be used to secure the pump cable to the downhole equipment (fig. 22), as tape and other adhesive products can leave a residue which may adversely affect some types of geochemical sampling. Even if geochemical sampling is not to be conducted at a particular field site, the downhole equipment may eventually be used at other field sites where such considerations are warranted.

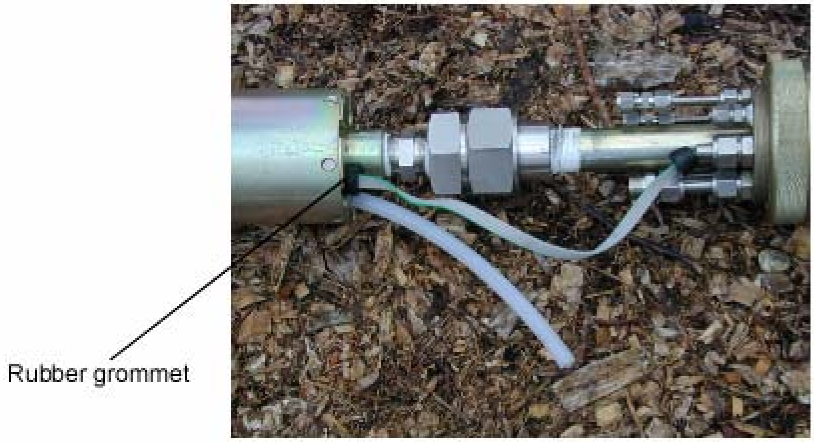

Figure 21. Photograph of a rubber grommet used to prevent the pump cable from rubbing on the metal plates of the pump shroud and the transducer shrouds.

If fluid-injection testing is to be conducted or a tracer solution is to be injected as part of downhole testing, the fluid-injection apparatus is placed below the pump apparatus and connected using the union ball fittings. If fluid-injection testing or tracer testing is not be conducted, then the fluid-injection apparatus does not need to be included in the configuration of the downhole components of the Multifunction BAT^3 (fig. 9).

An extension rod can be placed below the fluid-injection apparatus (if fluid-injection or tracer testing is to be conducted), or the pump apparatus (if fluid-injection or tracer testing is not conducted). The extension rod allows the length of the test interval (fig. 9) to be changed depending on the borehole conditions; additional information about the length of the test interval is given in the sections “4.8 Test-Interval Length” on page 34 and “9.4 Lowering the Downhole Components in a Borehole” on page 84. The user is responsible for supplying a 1-inch-diameter pipe of the desired length with NPT threads on either end. A spare union ball fitting is shipped in Box 1 of the Multifunction BAT^3. The two parts of the union ball fitting should be placed on the ends of the 1-inch-diameter pipe, and the union ball fitting is used to connect the extension pipe to the component above it (fig. 23).

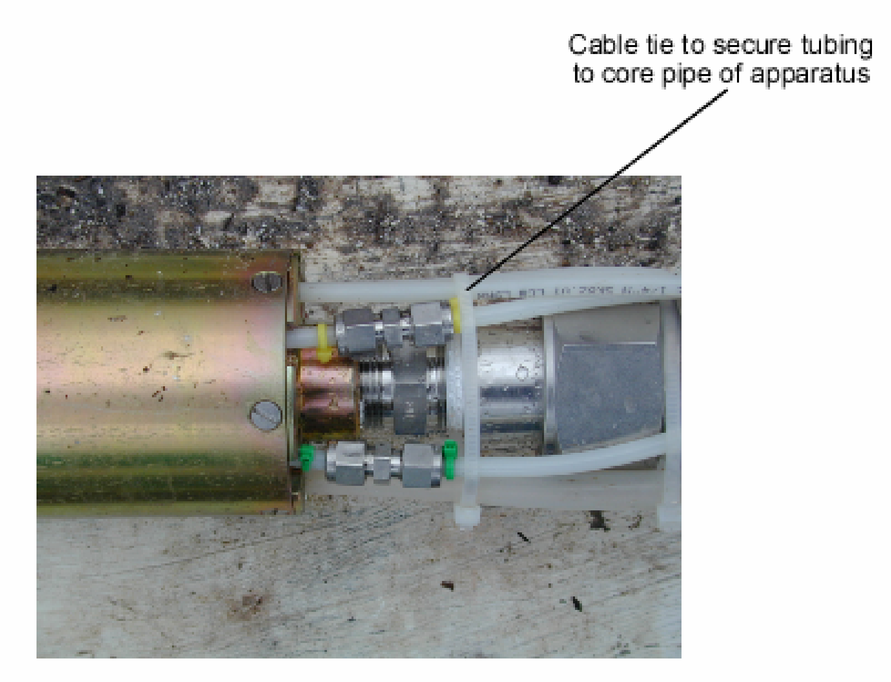

Figure 22. Photograph of cable ties used to secure the pump cable and tubing to the core pipe of the downhole apparatus.

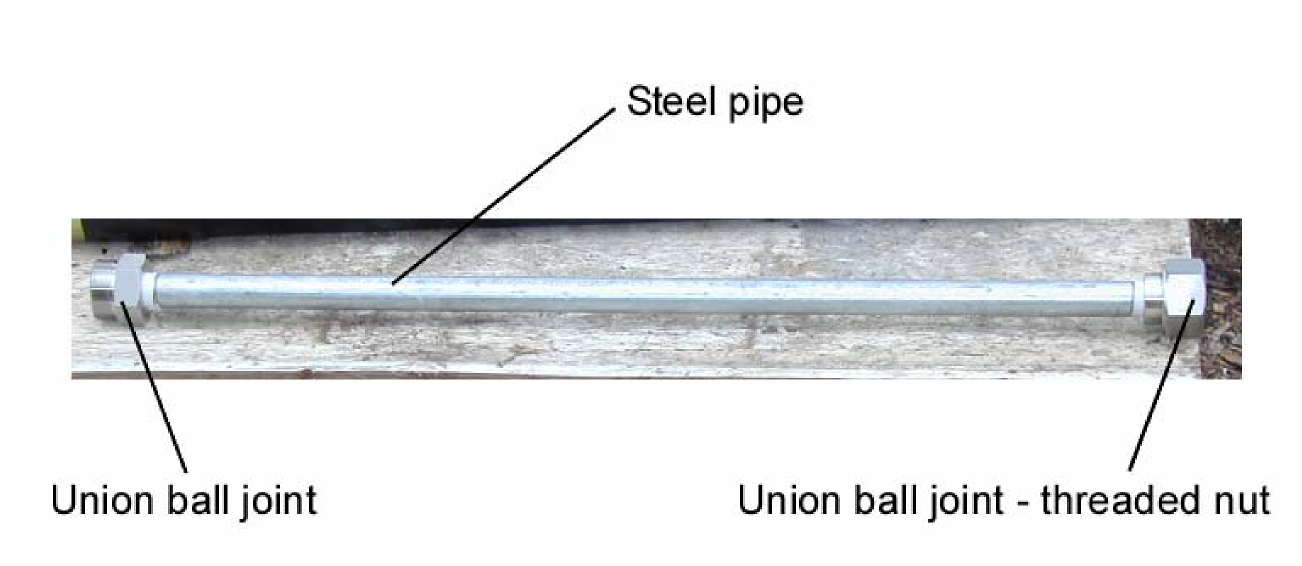

Figure 23. Photograph of an extension rod with parts of the union ball fitting connected on each end.

The bottom packer is placed below the extension rod and connected using the union ball fitting. If an extension rod is not used, the bottom packer is connected to either the pump apparatus or the fluid-injection apparatus, depending on the type of testing that is to be conducted with the Multifunction BAT^3.

Prior to connecting the downhole components of the Multifunction BAT^3 in preparation for deploying the equipment in the borehole, the user must consider the total length of the downhole equipment and the height of the hoisting apparatus that will be used to raise and lower the downhole equipment in the borehole. If the hoisting apparatus can accommodate the entire length of the downhole equipment, then the downhole components of the Multifunction BAT^3, including the tubing, can be assembled on the ground adjacent to the borehole. If, however, the total length of the downhole components of the Multifunction BAT^3 is longer than the height of the hoisting apparatus, the borehole components and tubing will have to be connected as the components are lowered in the borehole. The transducer shrouds, the top packer, and the pump shroud, however, will need to be connected using the union ball fittings prior to deploying this equipment in the borehole, as these components cannot be lowered in the borehole separately, because the pump cable is threaded through them. The other components are connected at the union ball fittings as the equipment is lowered in the borehole. In connecting components, the nut on the union ball fitting is used to tighten the connection so that the components, themselves, do not have to be rotated. The components at the bottom of the downhole configuration of the Multifunction BAT^3 will have to be lowered in the borehole first, and the proper tubing connections will have to be made. Under these circumstances it is best to have the downhole components of the Multifunction BAT^3 configured on the ground along with the necessary tubing in the order that they will be lowered into the borehole. The section “9.4 Lowering the Downhole Components in a Borehole” on page 84 provides further details on deploying the downhole components in a borehole.

4.8 Test-Interval Length

The test interval is defined as the distance from the bottom of the inflatable bladder on the top packer to top of the inflatable packer bladder on the bottom packer (fig. 9). The test interval with just the pump apparatus between the two packers is approximately 5.0 ft in length. If the fluid-injection apparatus is also placed between the two packers, the test interval will be approximately 6.2 ft in length. These dimensions are the minimum test interval dimensions for these configurations of the downhole equipment. The user should check these dimensions after the equipment has been assembled, as the dimensions my change slightly. The dimensions of the test interval and the components of the downhole equipment are important when locating the downhole equipment at the proper location to conduct tests in boreholes.

Borehole conditions and the fracturing along the borehole length will dictate the length of the test interval to be used. The test interval can be increased by adding an appropriate length of 1-inch-diameter steel pipe (with NPT threads) immediately above the bottom packer. A spare union ball fitting is shipped in Box 1 of the Multifunction BAT^3. The two parts of the union ball fitting are placed on the ends of the 1-inch-diameter pipe and the union ball fitting is used to connect the pipe to the component above it (either the pump apparatus or the fluid-injection apparatus) and the bottom borehole packer. Additional information about choosing an appropriate length for test intervals is discussed in the sections “7.1 Borehole Geophysical Logs” on page 62 and “9.4 Lowering the Downhole Components in a Borehole” on page 84.

4.9 Connecting Tubing

Tubing extending from land surface to the downhole equipment is used to operate the packers, the transducer “bleed” valves, and the fluid-injection valve. Tubing extending from land surface also is used to inject water into the test interval through the fluid-injection valve, and route water to land surface from the submersible pump in the pump shroud. The middle- and bottom-zone fluid pressure transducers in the transducer apparatus above the top packer also are connected to these intervals using tubing. The proper and safe operation of the downhole equipment requires that pressure-tight fittings be made to insure that there are no leaks in the tubing. In addition, it is extremely important that the user knows which tubing at land surface is connected to each of the downhole components; color coding the tubing is recommended for this purpose. One method of color coding the tubing is to use color plastic cable ties that can be attached at the ends of the tubing (fig. 24). Plastic cable ties are available from most electrical supply companies.

Figure 24. Photograph of colored plastic cable ties used to identify the tubing connected to the downhole components of the Multifunction BAT^3.

The pressure-tight tubing connections are made using Swagelok fittings (fig. 25). In general, 0.25-inch- and 0.50-inch-diameter tubing is used in the Multifunction BAT^3, and 0.25-inch and 0.50-inch Swagelok fittings are used to connect this tubing. The tubing to be used in configuring the Multifunction BAT^3 needs to be supplied by the user (see the section “7.6 Tubing and Tubing Connections” on page 65). The tubing material will depend on the geochemical conditions and the need for decontamination procedures when using the Multifunction BAT^3 for various applications. Not all of the tubing needs to be of the same material. For example, the tubing connected to the pump to route water to land surface may be constructed of one material, whereas, the tubing used for inflating packers and operating downhole valves may be constructed of another material.

In the following sections, the tubing connections to the various downhole components are described; the tubing and cable connections to equipment at land surface are discussed in the section “4.10 Summary of Cables and Tubing Extending to Land Surface” on page 40. Tubing that is connected between the downhole components should be threaded through the fluid-injection, pump, and transducer shrouds, when necessary; placing the tubing outside these shrouds will result in damage to the tubing and possible damage to the downhole components of the Multifunction BAT^3. Holes in the top and bottom plates of the fluid-injection, pump, and transducer shrouds allow for tubing to be threaded through the cylinders of the shrouds (fig. 10).

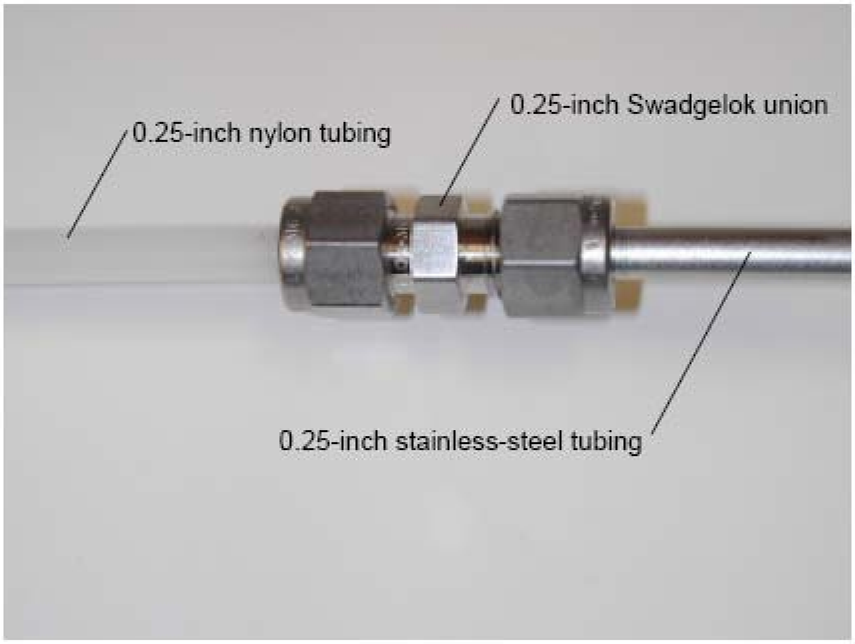

Figure 25. Photograph of a typical Swagelok pressure-tight fitting used to connect tubing.

4.9.1 Bottom Packer

Tubing (0.25-inch diameter) is connected to the inflation port at the top of the bottom packer. This tubing extends from the inflation port of the bottom packer, through the fluid-injection and the pump shrouds and connects to the bottom of a 0.25-inch-diameter stainless-steel tube extending through the top packer. At the top of the same stainless-steel tube in the top packer, 0.25-inch-diameter tubing is attached and fed through the transducer shrouds and extends to land surface.

4.9.2 Fluid-Injection Valve - Water Line

Tubing (0.5-inch diameter) is connected to the 0.5-inch diameter stainless-steel tubing extending from the top of the fluid-injection shroud. This tubing extends through the pump shroud and connects to the bottom of a 0.5-inch-diameter stainless steel tube extending through the top packer. At the top of the same stainless-steel tube in the top packer, 0.5-inch-diameter tubing is attached and fed through the transducer shrouds and extends to land surface.

If the Multifunction BAT^3 is not configured with the fluid-injection apparatus, then this tubing is not necessary. The 0.5-inch diameter stainless-steel tube in the top packer that would normally be used for this function should then be capped at both ends with pressure-tight Swagelok fittings to avoid hydraulic communication through the top packer.

4.9.3 Fluid-Injection Valve - Air Actuator

Tubing (0.25-inch diameter) is connected to the 0.25-inch diameter stainless-steel tubing extending from the top of the fluid-injection shroud. This tubing extends through the pump shroud and connects to the bottom of a 0.25-inch-diameter stainless steel tube extending through the top packer. At the top of the same stainless-steel tube in the top packer, 0.25-inch-diameter tubing is attached and fed through the transducer shrouds and extends to land surface.

If the Multifunction BAT^3 is not configured with the fluid-injection apparatus, then this tubing is not necessary. The 0.25-inch diameter stainless-steel tube in the top packer that would normally be used for this function should then be capped at both ends with pressure-tight Swagelok fittings to avoid hydraulic communication through the top packer.

4.9.4 Pump Discharge - Water Line

A continuous piece of 0.5-inch-diameter tubing is connected between the 0.5-inch-diameter Swagelok fitting housed in the pump shroud (fig. 15) and the bottom of a 0.5-inch-diameter stainless-steel tube extending through the top packer. It will be necessary to remove the cylinder of the pump shroud from the top plate of the shroud to gain access to the 0.5-inch-diameter Swagelok fitting in the pump shroud; the cylinder is removed from the top plate of the pump shroud by removing the screws that connect the cylinder to the top plate. At the top of the stainless-steel tube in the top packer, 0.5-inch-diameter tubing is attached and fed through the transducer shrouds and extends to land surface.

If the submersible pump in the Multifunction BAT^3 is not to be used in downhole testing, then this tubing is not necessary. The 0.5-inch diameter stainless-steel tube in the top packer that would normally be used for this function should then be capped at both ends with pressure-tight Swagelok fittings to avoid hydraulic communication through the top packer. In addition, the 0.5-inch-diameter tube extending from the pump in the pump shroud should be capped with a pressure-tight Swagelok fitting.

If the operation of the submersible pump is to be used to conduct hydraulic tests to estimate hydraulic properties of the test interval, an in-line check valve can be connected along the 0.5-inch pump-discharge tube. The check valve prohibits water in the pump discharge tube (above the check valve) from re-entering the test interval once the pump ceases to operate. This allows fluid pressure responses in the test interval during the recovery phase of the test (after pumping ends) to be more easily interpreted. If the check valve is not in place, at the end of pumping, water in the pump discharge tube extending to land surface will drain back into the test interval, resulting in a hydraulic perturbation on the fluid pressure recovery after pumping ends.

In this configuration of the Multifunction BAT[3], a Swagelok in-line check valve (SS-CHS8-1) with 0.5-inch Swagelok fittings at both ends and a 1 psi cracking pressure is connected at the bottom of a 0.5-inch-diameter stainless-steel tube that extends through the top packer (fig. 26). This stainless steel tube in the top packer is used to route water from the pump to land surface. Tubing (0.5-inch diameter) extending from the pump in the pump shroud is connected to the bottom of the check valve.

If water samples are to be collected for geochemical analyses from the submersible pump, and the ground water is likely to contain contaminants that require special disposal procedures if the water is discharged at land surface, the check valve should not be placed in the 0.5-inch-diameter tube leading from the submersible pump. The check valve will trap the contaminated ground water in the discharge tubing above the pump, and this water will need to be disposed of properly when the borehole testing equipment is removed from the borehole. Without the check valve in the tubing leading from the submersible pump, the water in the tubing at the time the pump is turned off will re-enter the test interval through the pump intake in the pump shroud.

Figure 26. Photograph of an in-line check valve in the pump discharge tubing that is connected at the bottom of a 0.5-inch-diameter stainless-steel tube extending through the top packer; the bottom of the check valve is connected to the 0.5-inch-diameter tubing that extends from the submersible pump.

4.9.5 Top Packer

Tubing (0.25-inch diameter) is connected to the inflation port at the top of the top packer. This tubing is fed through the transducer shrouds and extends to land surface.

4.9.6 Transducer “Bleed” Valves

Tubing (0.25-inch diameter) extending to land surface is connected to the 0.25-inch-diameter stainless-steel tube at the top of the transducer shrouds. This tube is connected to the transducer “bleed” valves in the transducer shrouds.

4.9.7 Middle-Zone Transducer

Two stainless-steel tubes extend from the bottom of the transducer shrouds, one marked with a yellow plastic strip, and one marked with a green plastic strip. The tube with the yellow plastic strip is connected to the middle-zone transducer, and the tube with the green plastic strip is connected to the bottom-zone transducer. To connect the middle-zone transducer to the middle zone, 0.25-inch-diameter tubing is used to connect the 0.25-inch-diameter stainless-steel tube (with the yellow strip) at the bottom of the transducer shrouds with the top of a 0.25-inch-diameter stainless-steel tube that extends through the top packer. The bottom of the same stainless-steel tube extending through the top packer is left open so that there is hydraulic communication to the middle-zone transducer.

4.9.8 Bottom-Zone Transducer

To connect the bottom-zone transducer to monitor below the bottom packer, 0.25-inch-diameter tubing is used to connect the 0.25-inch-diameter stainless-steel tube (with the green strip) at the bottom of the transducer shrouds with the top of a 0.25-inch-diameter stainless-steel tube that extends through the top packer. At the bottom of the same stainless-steel tube extending through the top packer, 0.25-inch-diameter tubing is connected and fed through the pump and fluid-injection shrouds and connected to 0.25-inch-diameter stainless-steel tubing extending through the bottom packer. The bottom of this stainless-steel tube in the bottom packer is left open so that there is hydraulic communication to the bottom-zone transducer.

4.9.9 Securing Tubing in the Downhole Equipment

In connecting tubing to the downhole components of the Multifunction BAT^3, it is important to secure the tubing so that it cannot be damaged when the downhole components are raised or lowered in the borehole. Tubing that is not tightly secured to the downhole equipment can be damaged on rough sections of the borehole, which may result in damage to the equipment, or the equipment becoming lodged in the borehole, or not operating properly. Tubing should be secured tightly to the center pipe of the apparatus. Also, in connecting the tubing at various locations along the downhole components, tubing should be threaded through the transducer, pump, and fluid-injection shrouds. Tubing placed on the exterior of the shrouds will become damaged as the equipment is lowered in the borehole. Plastic cable ties should be used to secure the tubing to the downhole equipment, as tape and other adhesive products can leave a residue which may adversely affect some types of geochemical sampling. Even if geochemical sampling is not to be conducted at a particular field site, the downhole equipment may eventually be used at other field sites where such considerations are warranted.

Prior to connecting the tubing between the downhole components of the Multifunction BAT^3 for deploying the equipment in the borehole, the user must consider the total length of the downhole equipment and the height of the hoisting apparatus that will be used to raise and lower the downhole equipment in the borehole. If the hoisting apparatus can accommodate the entire length of the downhole equipment, then the downhole components of the Multifunction BAT^3 can be assembled on the ground adjacent to the borehole, and the tubing connections can be made and secured with the equipment horizontal on the ground. If, however, the total length of the downhole components of the Multifunction BAT^3 is longer than the height of the hoisting apparatus, the borehole components and tubing will have to be connected as the components are lowered in the borehole. A discussion of the assembling and deploying the borehole components is given in the sections “4.7 Connecting Downhole Components” on page 29, and “9.4 Lowering the Downhole Components in a Borehole” on page 84.

4.10 Summary of Cables and Tubing Extending to Land Surface

After the downhole components of the Multifunction BAT^3 have been connected with the union ball fittings and tubing connections have been made between components, the downhole equipment of the Multifunction BAT^3 is ready to be deployed down a borehole. The following is a summary of the tubing and cables that would extend to land surface from the downhole equipment for different testing configurations of the Multifunction BAT^3. The descriptions that follow do not include the cable for the transducer to monitor above the top packer. The transducer to monitor the top interval is not connected to the downhole equipment of the Multifunction BAT^3; it is lowered in the borehole separately after the downhole equipment has been placed at the desired depth in the borehole.

4.10.1 Pumping and Fluid Injection

If both pumping and fluid injection are to be conducted, the downhole components of the Multifunction BAT^3 should have two transducer cables (middle and bottom zones), the pump cable, two (2) 0.5-inch-diameter tubes, and four (4) 0.25-inch-diameter tubes capable of extending to land surface after the equipment is lowered in the borehole. The 0.5-inch-diameter tubes are for fluid injection and the discharge from the pump, and the four (4) 0.25-inch-diameter tubes are for inflating the top and bottom packers, and operating the transducer “bleed” valves and the fluid-injection valve.

4.10.2 Pumping Without Fluid Injection

If the injection of fluid from land surface is not to be conducted in downhole testing, then the fluid-injection apparatus does not need to be placed below the pump apparatus in the configuration of the downhole components of the Multifunction BAT^3. This configuration of the downhole equipment should have two transducer cables (middle and bottom zones), the pump cable, one 0.5-inch diameter tube, and three 0.25-inch-diameter tubes capable of extending to land surface after the equipment is lowered in the borehole. The 0.5-inch-diameter tube is for the pump discharge, and the three 0.25-inch-diameter tubes are for inflating the top and bottom packers, and operating the transducer “bleed” valves.

4.10.3 Fluid Injection Without Pumping

If fluid injection from land surface is to be conducted, but pumping is not to be conducted, then the downhole components of the Multifunction BAT^3 should have two transducer cables (middle and bottom zones), the pump cable, one 0.5-inch diameter tube, and four 0.25-inch-diameter tubes capable of extending to land surface after the equipment is lowered in the borehole. The 0.5-inch-diameter tube is for fluid injection, and the four 0.25-inch-diameter tubes are for inflating the top and bottom packers, and operating the transducer “bleed” valves and the fluid-injection valve. Even though pumping will not be conducted, the pump cable still extends to land surface because the pump apparatus is not removed from the downhole components.

5. Downhole Control and Data-Acquisition Equipment

The tubing and cables extending up the borehole from the downhole components of the Multifunction BAT^3 are connected to data-acquisition and downhole-control equipment. The downhole-control equipment consists of a pressure manifold used to direct compressed gas to packers and valves in the downhole equipment, and an in-line pressure regulator to regulate air pressure at the water surface of a fluid reservoir tank for fluid injection into the test interval. The data-acquisition equipment consists of flowmeters to monitor rates of pumping or fluid injection, a data-acquisition panel for recording digital records of flow rates and fluid pressure from the transducers, and a panel of batteries to operate the data-acquisition equipment. The configuration of downhole-control and data-acquisition equipment is shown in figure 27.

5.1 Pressure Manifold

The top and bottom packers, transducer “bleed” valves, and fluid-injection valve are operated with compressed gases. A manifold to distribute compressed gas from a single pressure source to the downhole equipment is supplied with the Multifunction BAT^3 (fig. 28). The manifold has four separate outlets to distribute the compressed gas from a single source. The four outlets from the pressure manifold are used to operate the top packer, bottom packer, transducer “bleed” valves, and fluid-injection valve. The pressures to be applied to these components are discussed in the sections “4.2.2 Middle- and Bottom-Zone Transducers” on page 21, “4.5 Fluid-Injection Apparatus” on page 27, “9.7 Inflating Packers to Initiate a Test” on page 89, and “9.8 Deflating Packers to End a Test” on page 91. If fluid injection is not to be conducted, then one of the outlets on the pressure manifold is not used. Each outlet on the pressure manifold is controlled separately with a three-way valve, and each outlet has a separate pressure gage to view the pressure applied to the downhole equipment. A separate control valve and pressure gage on the manifold is used to control the compressed gas from the source, which can be a compressor or a cylinder of compressed gas.

The source of compressed gas is routed to the manifold through 0.25-inch Swagelok fitting on the back of the manifold box. The 4 outlets of compressed gas are also on the back of the manifold box; each outlet is a 0.25-inch Swagelok fitting.

The source of compressed gas on the pressure manifold is operated from a three-way valve with the settings, “Pressure from Source,” “Close” and “Vent Source.” Setting the valve on “Pressure from Source” means that the valve is open and compressed gas from the source can enter the manifold and be routed to the various outlets, whereas “Close” means the valve is closed and the manifold is not accepting compressed gas from the source. “Vent Source” means the pressure from the tubing entering the manifold from the pressure source will be vented out of the manifold. This setting isolates the pressure source from the other valves of the pressure manifold. The setting “Vent Source” should be used prior to disconnecting the tubing between the manifold and pressure source, so that pressure in this tubing is reduced to atmospheric pressure.

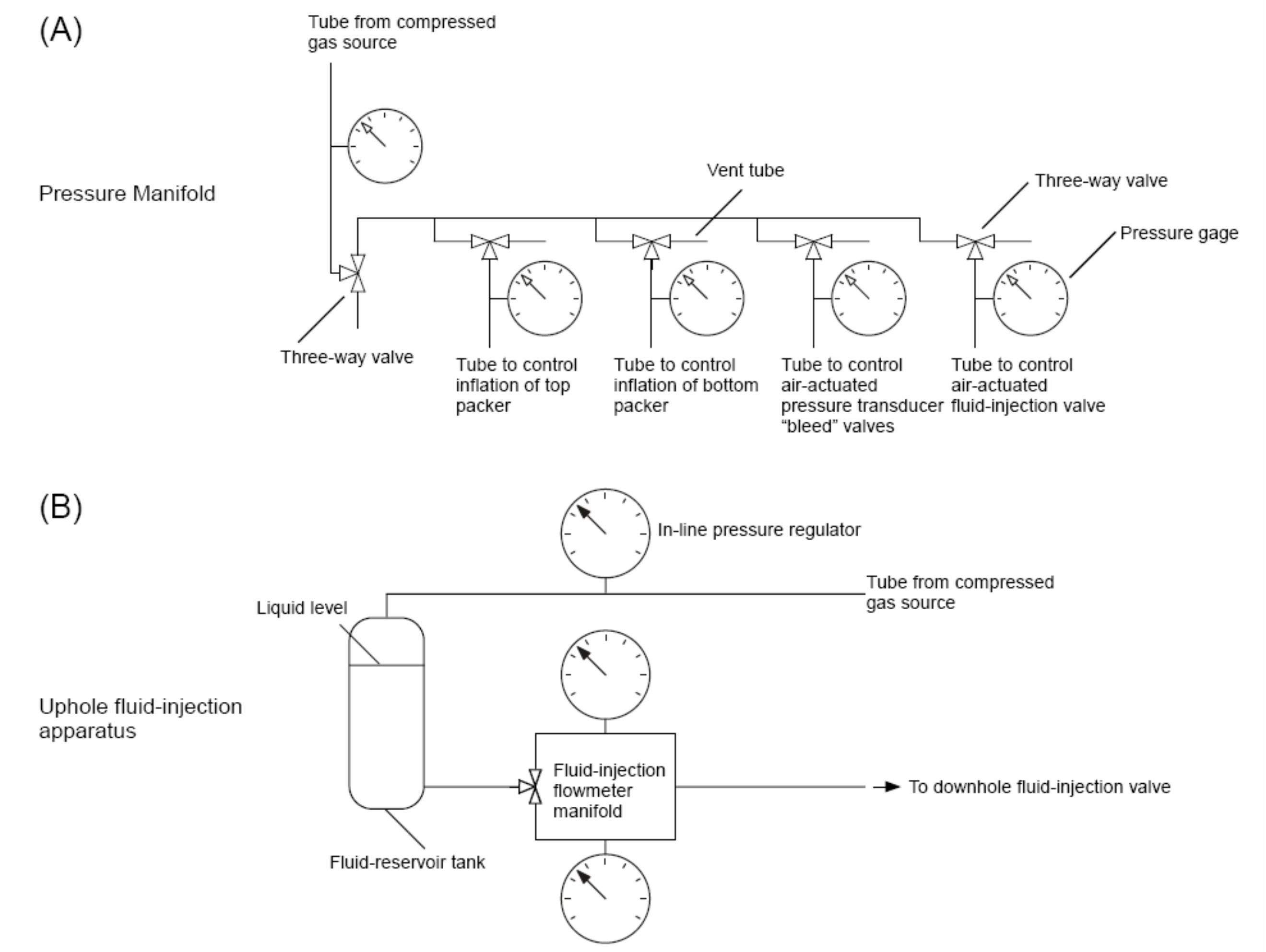

Figure 27. Schematic diagram of the downhole-control and data-acquisition equipment used by the Multifunction BAT^3, (A) pressure manifold, (B) uphole fluid-injection apparatus, (C) flowmeter for fluid discharge from the downhole pump, and (D) data-acquisition and power supply .

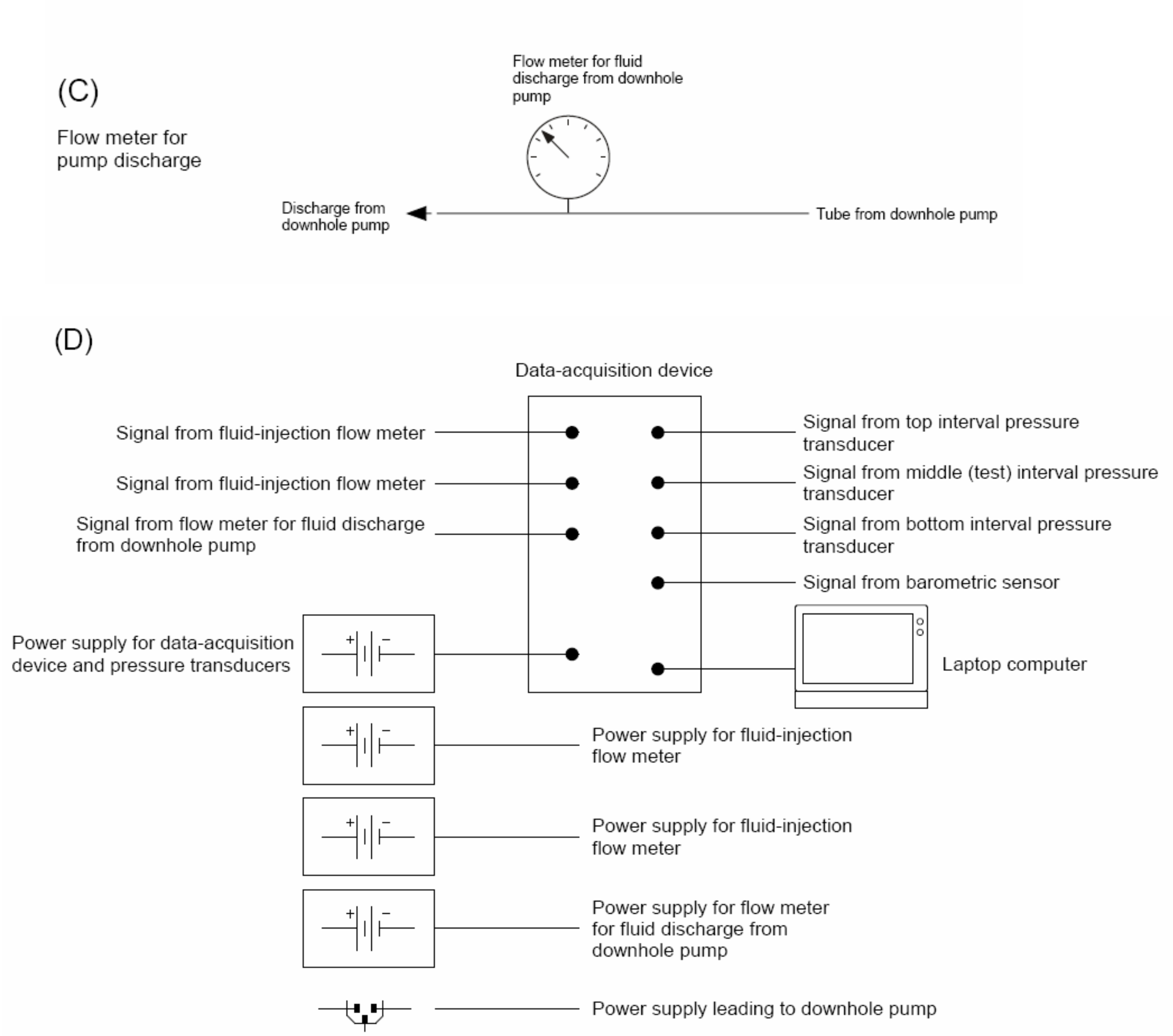

Figure 27. (cont.) Schematic diagram of the downhole-control and data-acquisition equipment used by the Multifunction BAT^3, (A) pressure manifold, (B) uphole fluid-injection apparatus, (C) flowmeter for fluid discharge from the downhole pump, and (D) data-acquisition and power supply .

Figure 28. Photograph of pressure manifold used to distribute compressed gas from a single source to the top and bottom packers, transducer "bleed" valves, and the fluid-injection valve.

Each outlet from the pressure manifold to a downhole component is operated by a separate three-way valve, with settings "Apply Pressure Downhole," "Close," and "Vent." The setting "Apply Pressure Downhole" connects the pressure source to the outlet associated with the valve that is being adjusted. The valve associated with the pressure source should be set on "Pressure from Source" to pressurize the downhole equipment attached to outlet. The "Close" setting for the valve on the pressure manifold closes the outlet and isolates it from the remainder of the manifold. The pressure applied to the downhole equipment can then be read on the pressure gage. Once the downhole component has been pressurized to the appropriate pressure, the valve on the pressure manifold should be kept on the "Close" setting to maintain the applied pressure and prevent the downhole components from being over pressurized with the pressure coming from the source of the compressed gas. Moving the valve to "Vent" isolates the valve from the remainder of the pressure manifold and opens the tubing connected to downhole equipment to atmosphere pressure to reduce the pressure applied to the downhole component.

5.2 In-Line Pressure Regulator

An in-line pressure regulator is supplied with the Multifunction BAT^3 (fig. 29). The in-line regulator is used to regulate pressure (greater than atmospheric pressure) applied to the water surface of a fluid reservoir tank during the injection of fluid into the test interval. In general, it is not necessary to apply a pressure greater than atmospheric pressure to the water surface of the fluid reservoir tank to inject fluid into the test interval. The height of the water in the fluid reservoir tank at land surface can act as the driving force to inject water through the fluid-injection tubing and the fluid-injection valve, and into the test interval between the two packers. Applying an air pressure greater than atmospheric pressure to the water surface of a fluid reservoir tank during fluid-injection testing is advantageous in estimating the hydraulic properties of fractures under different fluid-injection rates. An additional discussion of methods of conducting fluid-injection tests is given the sections "7.7 Fluid Reservoir Tank" on page 67 and "10.4 Single-Hole Hydraulic Test by Fluid Injection" on page 102.

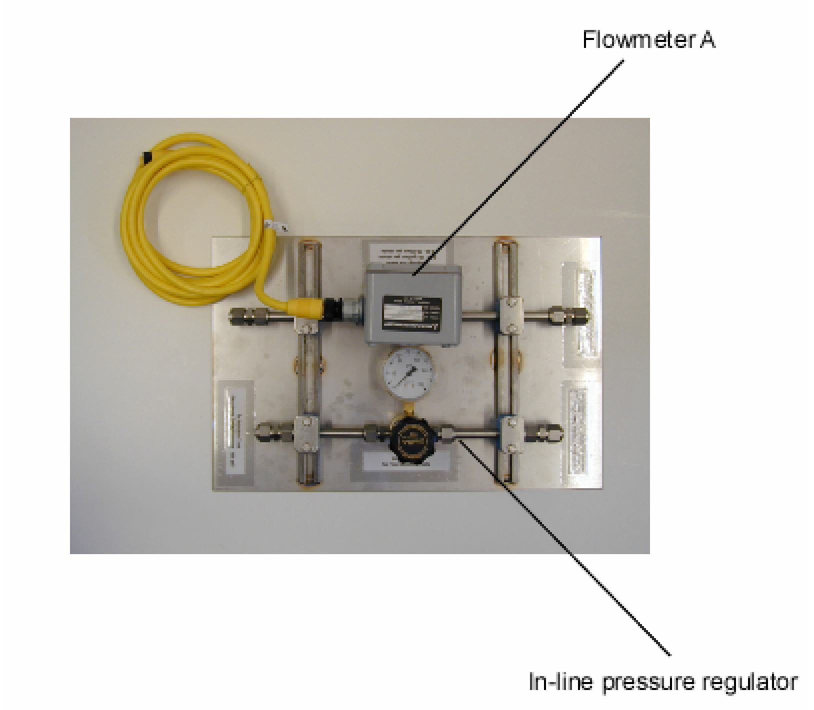

Figure 29. Photograph of the in-line pressure regulator used to regulate pressure (greater than atmospheric pressure) applied to the water surface of a fluid reservoir tank, and Flowmeter A used to monitor pumping rates from the submersible pump.

If a pressure greater than atmospheric pressure is to be applied to the water surface of the fluid reservoir tank, the inlet of the in-line regulator is connected to a source of compressed gas, such as cylinder of compressed gas or an air compressor, and the outlet is connected to a pressure-tight fitting above the water level in a fluid reservoir tank. Additional information about the configuration of a fluid reservoir tank is given in the sections “7.7 Fluid Reservoir Tank” on page 67 and “9.3 Preparing the Fluid Reservoir Tank for Fluid Injection” on page 83.

It is recommended that a compressor be used to supply compressed gas through the in-line regulator to the water surface of a fluid reservoir tank, as the in-line regulator will regulate pressure from the pressure source to achieve the prescribed pressure to be applied to the fluid reservoir; the excess pressure will dissipated out of the regulator. If a cylinder of compressed gas is used, the contents of the cylinder may be depleted rapidly, where as a gasoline-powered compressor can regenerate the pressure source. The maximum pressure that usually needs to be applied to the water surface of the fluid reservoir for fluid-injection testing is less than 60 psi, which is within the range of many gasoline-powered compressors.

The in-line regulator supplied with the Multifunction BAT^3 is an Air Products E11-141C in-line regulator. The maximum inlet pressure for this in-line regulator is 400 psi and the maximum outlet pressure is 100 psi.

5.3 Data-Acquisition Panel

The Multifunction BAT^3 comes with a data-acquisition panel on which there is a Campbell Scientific CR23X Data Logger (fig. 30). The data logger queries the pressure transducers and flowmeters at a predetermined interval and stores digital records of the responses from these sensors. The data-acquisition panel and the data logger are wired to interface with a barometric pressure sensor, three pressure transducers, two flowmeters, and three 12 V DC batteries to operate the data logger and the flowmeters. The data-acquisition panel has receptacles with pin contacts. The pressure transducers, flowmeters and batteries have screw-type coupling rings on their respective cables to connect with the appropriately labeled receptacle on the data-acquisition panel (fig. 31). The receptacles for the cables on the data-acquisition panel are labeled for the top-, middle- and bottom-zone transducers, the flowmeters, and the 12 V DC batteries that operate this equipment.

A barometric pressure sensor also is located on the data-acquisition panel. The barometric sensor is used to monitor the atmospheric pressure to correct the absolute pressure transducers for atmospheric pressure. The barometric sensor is directly wired to the Campbell Scientific CR23X Data Logger.

The data-acquisition panel also includes cables that connect the Campbell Scientific CR23X Data Logger to a 9-pin serial or a Universal Serial Bus (USB) port on a laptop computer (fig. 32). The programs that control the operation of the data logger are downloaded from the laptop computer to the data logger. The laptop computer also operates the BAT^3 Analyzer that is used to visualize and interpret the real-time responses of the pressure transducers and flowmeters during testing (Winston and Shapiro, 2007). The laptop computer is to be supplied by the user.

A data-acquisition program for the Campbell Scientific CR23X Data Logger has been written for monitoring the responses from the barometric sensor, the pressure transducers, and the flowmeters. The data-acquisition program can be forwarded to the user electronically. The BAT^3 Analyzer for visualizing and interpreting the data in real-time can also be forwarded to the user electronically. Additional information about the data acquisition programs for the data logger and the real-time visualization of data is given in the sections “8.1 Connecting the Laptop Computer to the Data Logger” on page 71, “8.3 Loading a Data-Acquisition Program” on page 73, “8.4 Changing the Sampling Interval” on page 74, “8.5 Raw Data Files” on page 75, and “8.6 Real-Time Data Visualization” on page 77.

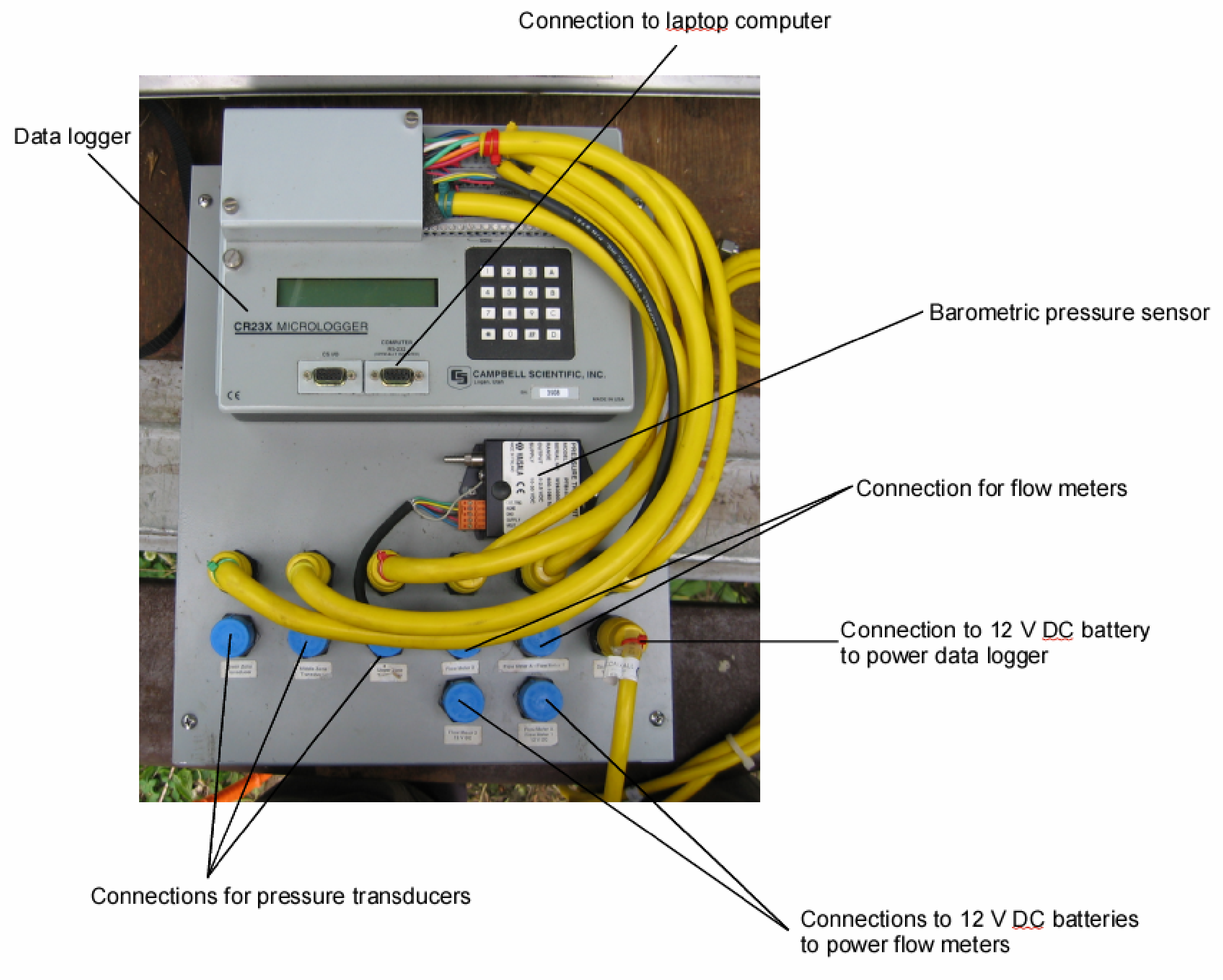

Figure 30. Photgraph of the data-acquisition panel of the Multifunction BAT^3 with a Campbell Scientific CR23X Data Logger wired to receptacles where sensors and sources of power are connected; a barometric sensor is also located on the data-acquisition panel and wired to the data logger.

Figure 31. Photographs of the cables with screw-type coupling rings used to connect pressure transducers, flowmeters, and batteries to the data-acquisition panel.

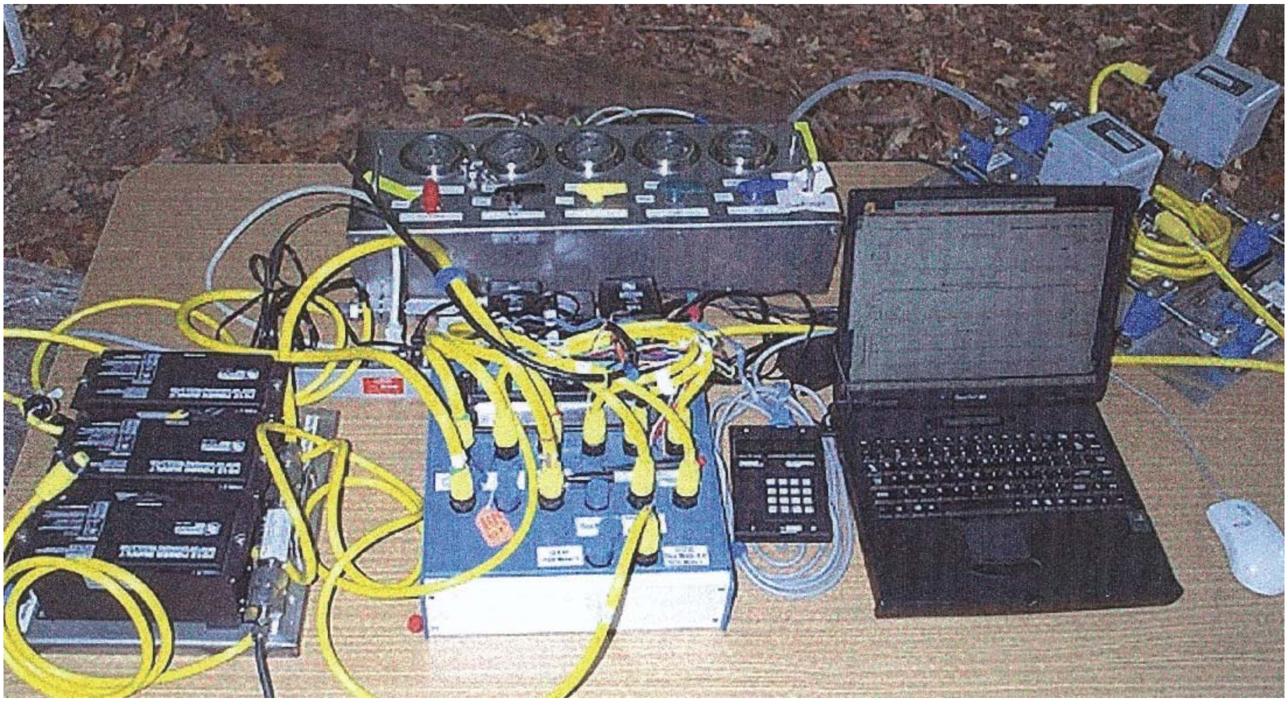

Figure 32. Photograph of a laptop computer connected to the Campbell Scientific CR23X Data Logger on the data-acquisition panel of the Multifunction BAT^3.

5.4 Flowmeter for Pumping

The flow rate from the submersible pump is monitored by connecting the 0.5-inch-diameter tubing leading from the pump through Flowmeter A. The 0.5-inch-diameter tubing from the pump is connected to the end of the flowmeter denoted as the water inlet (fig. 29). Flowmeter A is an FT-08NEXW-LED-5 EG&G Flow Technology Turbine Flowmeter that is attached to a EG&G Flow Technology CA03-4-C-000B6 signal conditioner that measures the frequency of the flowmeter impeller. Responses from the signal conditioner are relayed to the data logger on the data-acquisition panel. The yellow cable leading from the signal conditioner is attached to the data-acquisition panel. The yellow cable is used to supply 12 V DC power to the signal conditioner and relay responses from the signal conditioner to the data logger. The flow rate is calibrated to the frequency of the flowmeter impeller. Flowmeter A has a calibrated range from 0.24 to 10.4 gal/min. The factory calibration for Flowmeter A is given in table 4.

There is a linear relation between the impeller frequency and the flow rate for Flowmeter A. This is shown in figure 33, along with the equation relating impeller frequency to flow rate. This relation is used to convert the impeller frequency to flow rate, and it is the calibration that is included in the library of calibrations that comes with the BAT^3 Analyzer; the BAT^3 Analyzer is software used for real-time visualization of the pressure transducers and flowmeter responses during testing. The calibration given in table 4 and figure 33 is specific for the particular flowmeter that is included with the Multifunction BAT^3. The serial number of Flowmeter A should be check to insure that the proper calibration is applied to the flowmeter responses. The serial number of the flowmeter is engraved on the stainless-steel housing of the flowmeter impeller. If there are updates to the calibration of this flowmeter, or if there is a replacement for this flowmeter, the updated calibration will be included in the library of calibrations that accompanies the BAT^3 Analyzer.

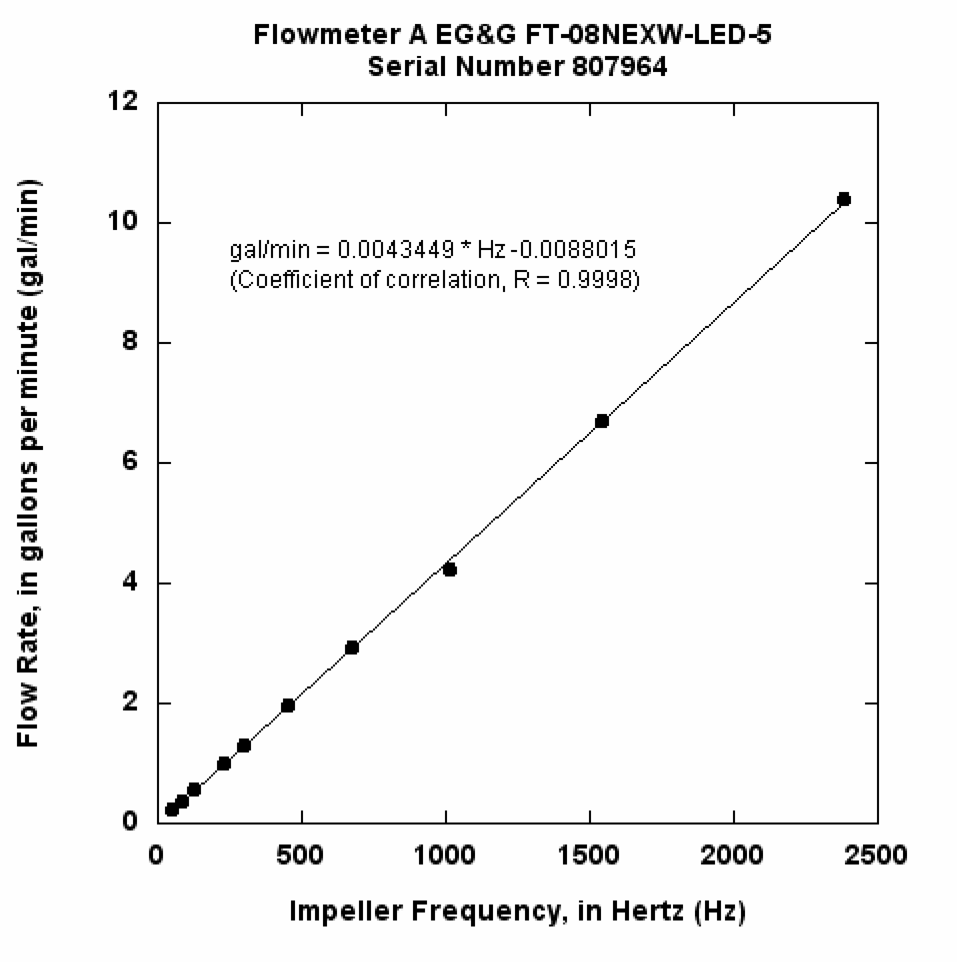

Figure 33. Diagram of the factory calibration showing the relation between the impeller frequency and the flow rate for Flowmeter A of the Multifunction BAT^3.

In some instances of geochemical sampling and aquifer testing, flow rates may be needed that are lower than the lower end of the range of Flowmeter A. In such instances, Flowmeter 1 could be used for measuring fluid withdrawals from the pump (fig. 34). Flowmeter 1 has a calibrated range from 0.048 to 2.0 gal/min. The Grundfos Rediflo2 pump system will support flow rates as low as 0.05 gal/min, but there may be some heating of the water in the test interval, because there may not be sufficient water flow around the pump to cool the pump motor. Flowmeter 1 is an FTO-5NIYW-LHC-5 EG&G Flow Technology Turbine Flowmeter that is attached to a EG&G Flow Technology CA03-4-C-000B6 signal conditioner that measures the frequency of the flowmeter turbine. Responses from the signal conditioner are relayed to the data logger on the data-acquisition panel. The yellow cable leading from the signal conditioner is attached to the data-acquisition panel. The yellow cable is used to supply 12 V DC power to the signal conditioner and relay responses from the signal conditioner to the data logger. Similar to the discussion of Flowmeter A, the flow rate for Flowmeter 1 is calibrated to the frequency of the impeller. The factory calibration for Flowmeter 1 is given in table 5 and the linear relation between the impeller frequency and the flow rate is shown in figure 35. This calibration is also included in the library of calibrations that accompanies the BAT^3 Analyzer. The calibration given in table 5 and figure 35 is specific for the particular flowmeter that is included with the Multifunction BAT^3. The serial number of Flowmeter 1 should be check to insure that the proper calibration is applied to the flowmeter responses. The serial number of the flowmeter is engraved on the stainless-steel housing of the flowmeter impeller. If there are updates to the calibration of this flowmeter, or if there is a replacement for this flowmeter, the updated calibration will be included in the library of calibrations that accompanies the BAT[3] Analyzer.

Flowmeter 1 is located on a plate with a three-way valve that can route water to either Flowmeter 1 or Flowmeter 2. Usually, Flowmeters 1 and 2 are used to measure fluid-injection rates. If Flowmeter 1 is to be used to measure flow from the submersible pump, the 0.5-inch-diameter tubing from the pump is attached to the fitting on the three-way valve. The valve on the flowmeter panel has three positions (fig. 36), (1) directed toward Flowmeter 1, (2) directed toward Flowmeter 2, and (3) closed. If the valve is not positioned as shown in figure 36, the flowmeters may not operate properly. To route the water to Flowmeter 1, the three-way valve should be directed to Flowmeter 1.

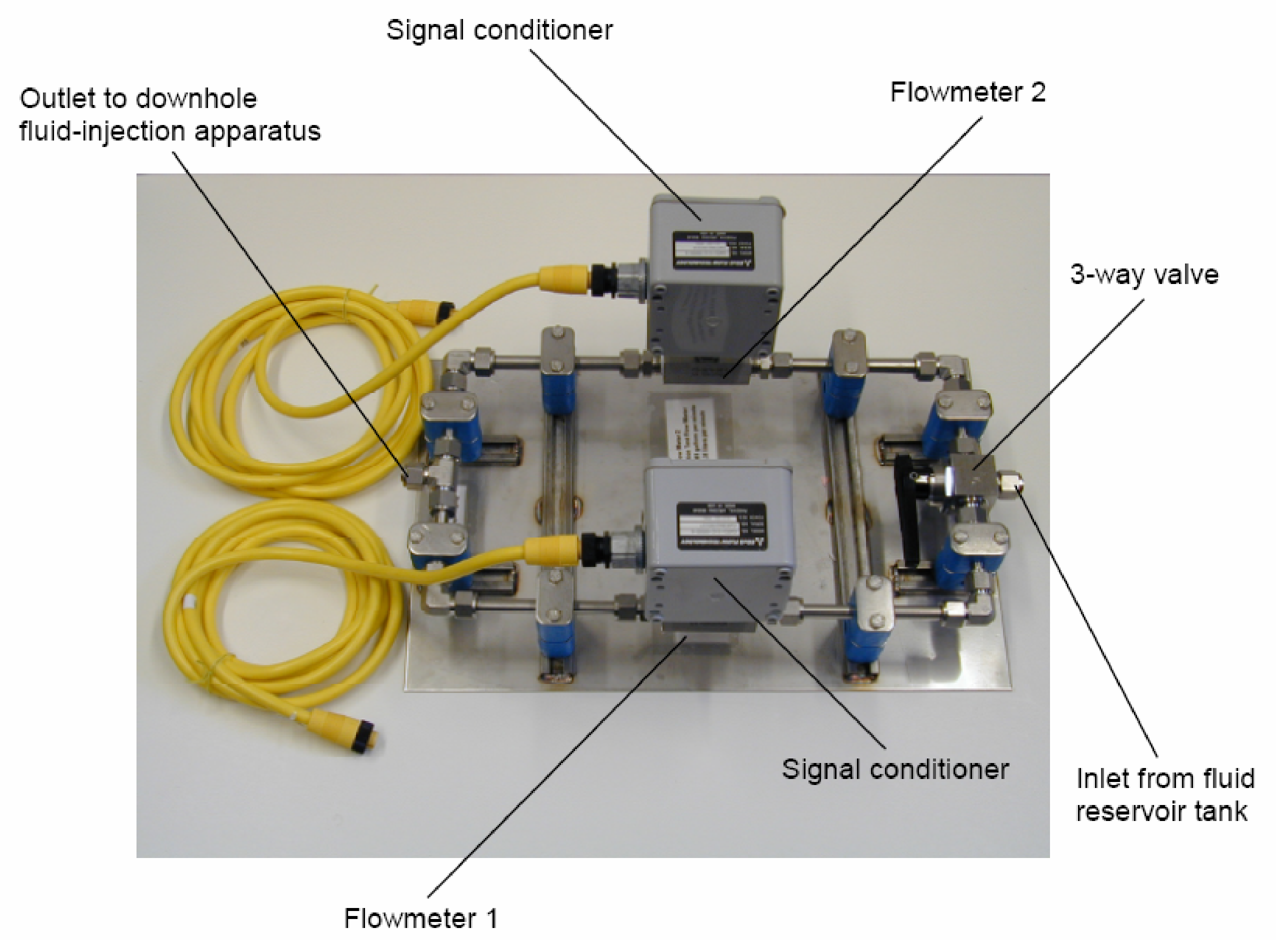

Figure 34. Photograph of Flowmetes 1 and 2 used to monitor fluid-injection rates; Flowmeter 1 can also be used to monitor the pump discharge for rate below the calibrated range of Flowmeter A.

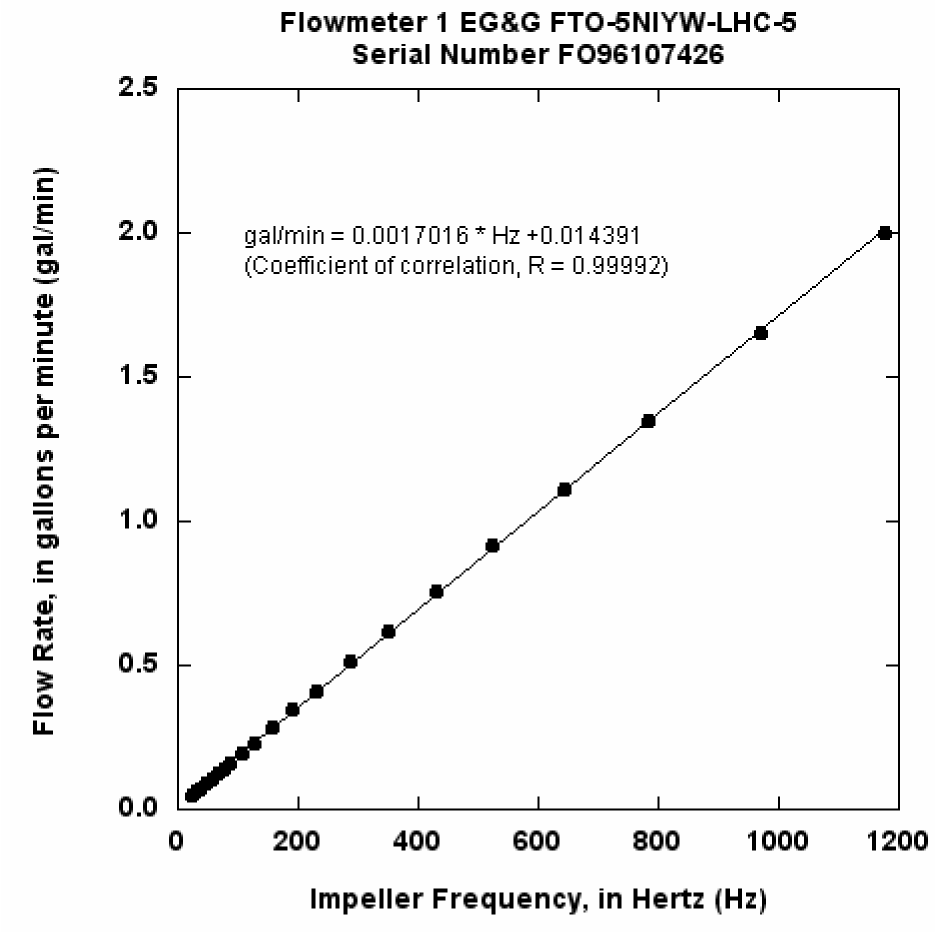

Figure 35. Diagram of the factory calibration showing the relation between the impeller frequency and the flow rate for Flowmeter 1 of the Multifunction BAT^3.

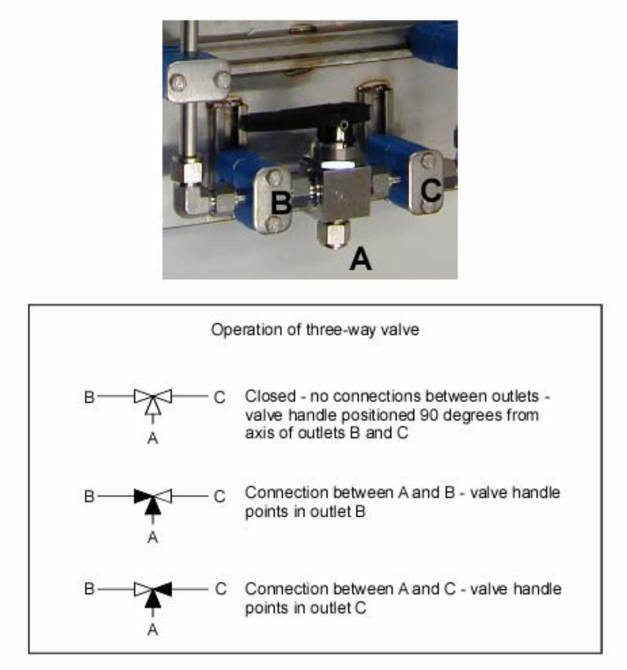

Figure 36. Photograph of the three-way valve that routes water to Flowmeter 1 or Flowmeter 2, and a schematic diagram of the operation of the three-way valve.s

Table 4. The Factory calibration performed on October 17, 1996, relating impeller frequency to flow rate for FT-08NEXW-LED-5 EG&G Turbine Flow Meter, Serial Number 807964 (Flowmeter A) of the Multifunction BAT[3].

Impeller Frequency, in Hertz	Flow Rate, in gallons per minute
2382.932	10.397
1540.137	6.706
1016.209	4.223
672.080	2.930
450.636	1.960
298.826	1.296
228.826	0.994
127.781	0.561
85.238	0.379
51.474	0.244

Table 5. Factory calibration performed on October 17, 1996, relating impeller frequency to flow rate for FTO-5NIYW-LHC-5 EG&G Turbine Flow Meter, Serial Number FO96107426 (Flowmeter 1) of the Multifunction BAT[3].

Impeller Frequency, in Hertz	Flow Rate, in gallons per minute
1175.642	2.003
969.214	1.656
784.150	1.350
642.176	1.112
524.808	0.915
429.203	0.755
349.890	0.621
286.315	0.513
228.597	0.412
191.444	0.347
156.532	0.284
127.667	0.232
105.475	0.193
87.395	0.159
76.611	0.141
66.398	0.124
57.187	0.108
47.503	0.0891
38.464	0.0726
31.689	0.0604
25.211	0.0481

5.5 Flowmeters for Fluid Injection

Fluid injection is usually conducted to test the hydraulic properties of low-permeability test intervals or to inject a tracer solution into a test interval. Two flowmeters are configured to measure a wide range of flow rates during fluid injection. For fluid injection, Flowmeters 1 and 2 are used (fig. 34). The choice of which flowmeter to use during the fluid injection will depend on the transmissivity of the test interval. Additional information about conducting fluid-injection tests is given in the section “10.4 Single-Hole Hydraulic Test by Fluid Injection” on page 102. The valve at the inlet to the flowmeters directs the flow to the chosen flowmeter (see fig. 36 and the discussion in the section “5.4 Flowmeter for Pumping” on page 49).

For fluid-injection testing, the water from a fluid reservoir tank is routed to the end of the panel of flowmeters with the three-way valve. At the other end of the plate holding the flowmeters, the 0.5-inch-diameter tube leading to the downhole fluid-injection valve is attached (fig. 27 and 34).

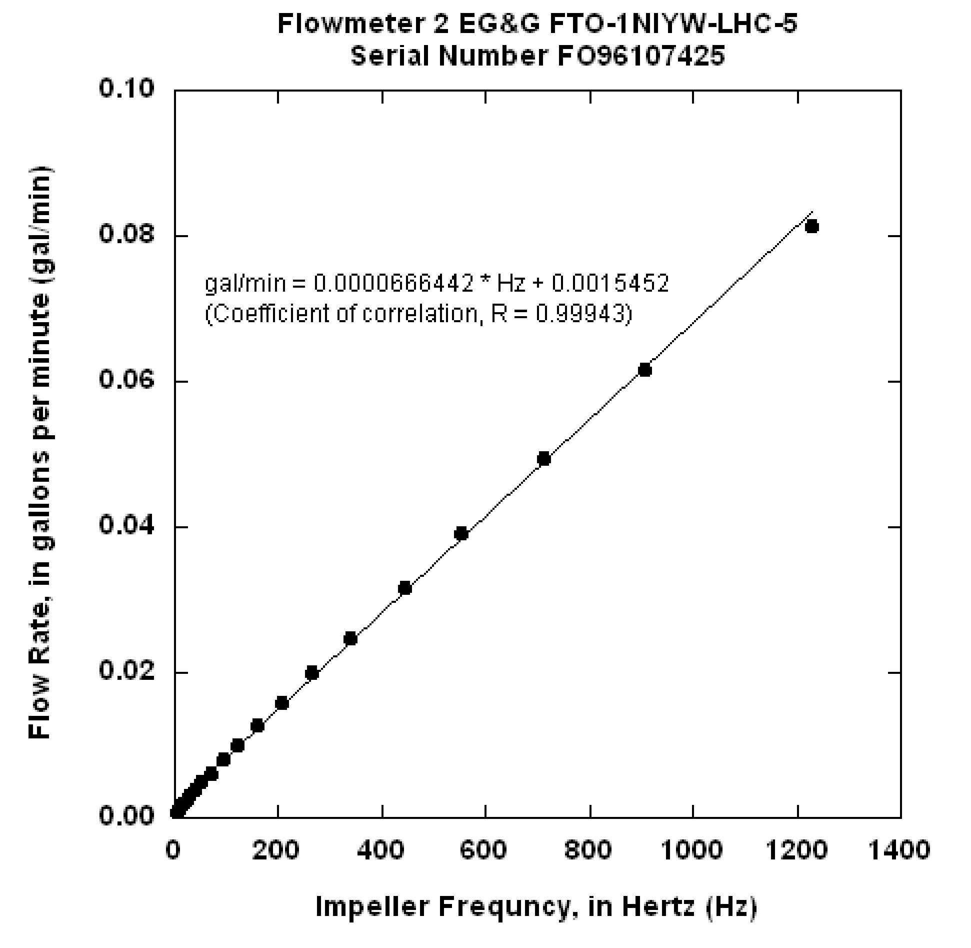

Figure 37. Diagram of the factory calibration showing the relation between the impeller frequency and the flow rate for Flowmeter 2 of the Multifunction BAT^3.

The specifications of Flowmeter 1 are given in the section “5.4 Flowmeter for Pumping” on page 49. Flowmeter 2 is a FTO-1NIYW-LHC-5 EG&G Flow Technology Turbine Flowmeter that is attached to a EG&G Flow Technology CA03-4-C-000B6 signal conditioner that measures the frequency of the flowmeter impeller. Responses from the signal conditioner are relayed to the data logger on the data-acquisition panel. The yellow cable leading from the signal conditioner is attached to the data-acquisition panel. The yellow cable is used to supply 12 V DC power to the signal conditioner and relay responses from the signal conditioner to the data logger. Flowmeter 2 has a calibrated range from 0.00088 to 0.081 gal/min. The factory calibration for Flowmeter 2 is given in table 6 and the linear relation between the impeller frequency and the flow rate is shown in figure 37. This calibration is also included in the library of calibrations that accompanies the BAT^3 Analyzer. The calibration given in table 6 and figure 37 is specific for the particular flowmeter that is included with the Multifunction BAT^3. The serial number of Flowmeter 2 should be check to insure that the proper calibration is applied to the flowmeter responses. The serial number of the flowmeter is engraved on the stainless-steel housing of the flowmeter impeller. If there are updates to the calibration of this flowmeter, or if there is a replacement for this flowmeter, the updated calibration will be included in the library of calibrations that accompanies the BAT^3 Analyzer.

5.6 Battery Panel

The Campbell Scientific CR23X Data Logger, and the flowmeters are powered by 12 V DC batteries. Three 12 V DC batteries are located on a battery panel (fig. 38). Each battery is enclosed in a case that includes a battery charger. The batteries are charged from 120 V AC power. Each battery has a connection for a pinned receptacle on the data-acquisition panel. The receptacles for the power supplied from the 12 V DC batteries are marked on the data-acquisition panel for the data logger and the flowmeters.

If only one flowmeter is in use, such as during geochemical testing or pumping for hydraulic tests, then two batteries need to be connected to the data-acquisition panel, one battery for the data logger, and one battery for the flowmeter. If fluid-injection testing is to be conducted using both flowmeters, then all three batteries need to be connected to the data-acquisition panel, one battery for the data logger and one battery for each of the flowmeters.

The batteries are charged by connecting the AC adapter to the pinned receptacle attached to the battery charger and connecting the charger to a 120 V AC power source. Three AC adapters are included in the Multifunction BAT^3 and are shipped in Box 5. The 12 V DC batteries can be charged from 120 V AC power at the same time that they are being used to operate the data logger and the flowmeters.

Table 6. calibration performed on October 17, 1996, relating impeller frequency to flow rate for FTO-1NIYW-LHC-5 EG&G Turbine Flow Meter, Serial Number FO96107425 (Flowmeter 2) of the Multifunction BAT[3].

Impeller Frequency, in Hertz	Flow Rate, in gallons per minute
1229.848	0.0815
906.911	0.0618
710.963	0.0495
553.077	0.0393
443.028	0.0317
337.345	0.0248
262.866	0.0199
205.244	0.0159
158.817	0.0127
119.445	0.00994
92.357	0.00797
69.321	0.00625
52.167	0.00495
39.184	0.00392
29.254	0.00310
23.229	0.00257
16.625	0.00198
12.015	0.00155
8.751	0.00123
5.371	0.00088

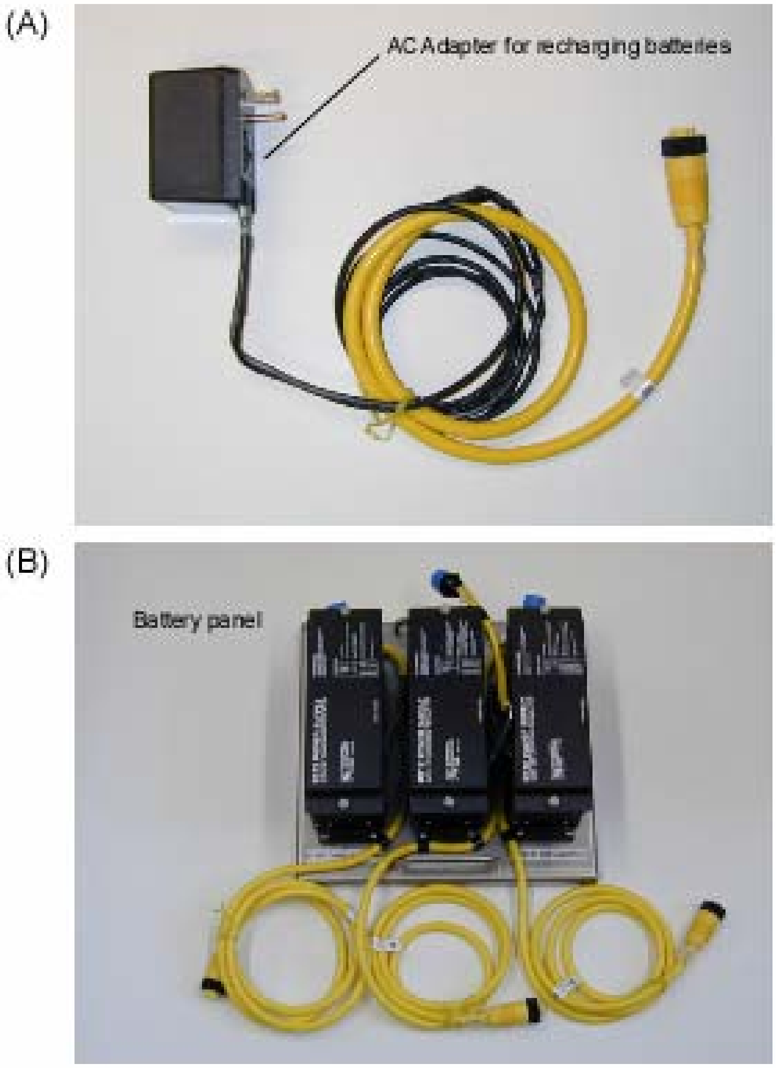

Figure 38. Photographs of (A) the AC adapter used to recharge batteries, and (B) the panel of 12 V DC batters used to power the data logger and flowmeters of the Multifunction BAT^3.

5.7 Summary of Connections to Data-Acquisition and Downhole-Control Equipment

After the downhole components of the Multifunction BAT^3 have been assembled at land surface, the tubing and electrical cables from the downhole components can be connected to the data-acquisition and downhole-control equipment. This section contains a summary of the tubing and electrical cable connections to the pressure manifold, data-acquisition panel, the flowmeters, and the fluid reservoir tank.

It is extremely important that the tubing and electrical cables are connected to the appropriate locations on the data-acquisition and downhole-control equipment. The safe operation of the downhole components relies on applying compressed gas to the packers and downhole valves in a proper sequence. Applying compressed gas to the wrong downhole component could damage the downhole equipment and could result in injury to the user. Color coding the tubing and electrical cables is recommended to avoid mistakes in connecting the tubing and electrical cables; plastic cable ties of various colors can be used for this purpose (fig. 24). The pressure transducers are already color-coded, with red, yellow and green for the top-, middle-, and bottom-zone transducers respectively.

5.7.1 Tubing Connections to the Pressure Manifold

The pressure manifold controls the distribution of compressed gas to operate downhole components of the Multifunction BAT^3. A source of compressed gas is connected to the pressure manifold and distributed to 4 outlets. The four outlets control the top and bottom packers, and the air actuators of the transducer "bleed" valves and the fluid-injection valve. If fluid-injection tests are not to be conducted, then one of the outlets of the pressure manifold is not needed.

Tubing from the downhole components are connected to the pressure manifold. It is extremely important that the tubing leading from the downhole equipment is labeled properly, otherwise compressed gas could be mistakenly applied to the wrong component, which could result in damaging the downhole equipment, the downhole equipment becoming stuck in the borehole, and possible injury to the equipment operators.

5.7.2 Tubing Connections to the Flowmeters

Three flowmeters are included in the Multifunction BAT^3. One of the flowmeters (Flowmeter A) is primarily used for monitoring fluid discharge from the pump and has a range from 0.24 to 10.4 gal/min. Tubing from the downhole pump is connected to the inlet of the flowmeter. Additional tubing is connected to the outlet of the flowmeter for collecting water samples for geochemical analyses and directing the water to a collection point for disposal.

Two flowmeters (Flowmeters 1 and 2) are arranged on a panel and connected with a three-way distribution valve. Flowmeters 1 and 2 are calibrated over a range from 0.048 to 2.0 gal/min and from 0.00088 to 0.081 gal/min, respectively. These flowmeters can be used to monitor pumping, or fluid injection from a fluid reservoir tank at land surface. If these flowmeters are to monitor the discharge from the pump, the discharge tubing from the pump is connected to the water inlet, and the three-way valve is positioned in the direction of the flowmeter that is to be used. Additional tubing is connected to the outlet of the flowmeter panel and directed to a collection point for sampling or disposal.

If Flowmeters 1 and 2 are to be used to monitor rates of fluid injection, 0.5-inch-diameter tubing is connected between the outlet of the fluid reservoir tank and the inlet of the flowmeter panel, and the 0.5-inch-diameter tubing from the downhole fluid-injection valve is connected to the outlet of the flowmeter panel. Water from the fluid reservoir can be routed through either of the flowmeters by using the three-way valve at the inlet to the flowmeter panel. The sections "5.4 Flowmeter for Pumping" on page 49 and "5.5 Flowmeters for Fluid Injection" on page 55 provide a discussion of the operation of the three-way valve for routing water through the flowmeters.

5.7.3 Tubing Connections to the Fluid Reservoir Tank

A fluid reservoir tank is used as a source of water for fluid-injection tests or tracer tests. A description of the fluid reservoir is given in the section "7.7 Fluid Reservoir Tank" on page 67. Tubing from the outlet of the fluid reservoir tank is connected to the three-way valve at the water inlet of the flowmeter panel. A fitting at the top of the fluid reservoir can be left open if the water is to be injected with only atmospheric pressure acting on the water surface of the fluid reservoir. If a pressure above atmospheric pressure is to be applied to the water surface in the fluid reservoir during fluid-injection or tracer tests, a fitting at the top of the fluid reservoir is connected to the outlet of the in-line pressure regulator and a source of compressed gas is connected to the inlet of the in-line pressure regulator.

5.7.4 Transducer Cables

The wires from the top-, middle- and bottom-zone transducers are connected to the receptacles for the appropriate transducer on the data-acquisition panel. The top-zone transducer is marked with red plastic cable tie, the middle-zone transducer is marked with a yellow plastic cable tie, and the bottom-zone transducer is marked with a green plastic cable tie. The data-acquisition panel has receptacles with pin contacts. The pressure transducers wires have coupling rings that screw onto these receptacles to secure the cable to the data-acquisition panel.

5.7.5 Flowmeter Cables

The yellow wires leading from the signal conditioner attached to the flowmeters are connected to the data-acquisition panel. These cables supply power to the signal conditioner and relay responses from the flowmeter to the data logger. Locations for attaching the cables from the flowmeters are marked on the data-acquisition panel for Flowmeter A and Flowmeters 1 and 2. Only two flowmeters can be connected to the data-acquisition panel at one time. The data-acquisition panel has pinned receptacles that accept the wires from the flowmeters. The cables from each flowmeter are connected to the appropriate locations marked on the data-acquisition panel, and the coupling ring on the cable is screwed to tighten the wire to the pinned receptacle on the data-acquisition panel.

5.7.6 Battery Panel

A panel of three 12 V DC batteries is used to supply power to the Campbell Scientific CR23X Data Logger and two flowmeters. Pinned receptacles on the data-acquisition panel are marked for batteries. The cables from the batteries have a coupling ring to tighten the battery cable to the receptacles on the data-acquisition panel.

The batteries can be connected to a 120 V AC power source to recharge the batteries. Batteries can be recharged as the equipment is being used for data acquisition. A pinned receptacle is attached to each battery for connection to the 120 V AC power adapter; three 120 V AC power adapters are shipped with the Multifunction BAT^3. The cable from the 120 V AC power adapters has a coupling ring to tighten the cable to the pinned receptacle attached to each battery for recharging.

6. Other Equipment Supplied

The Multifunction BAT^3 is shipped with other equipment used to deploy the downhole components and assist in conducting geochemical sampling and hydraulic testing in bedrock boreholes. This equipment includes a pressure regulator for cylinders of compressed gas, an electric water-level indicator, and a swivel-eye hoisting plug (fig. 39).

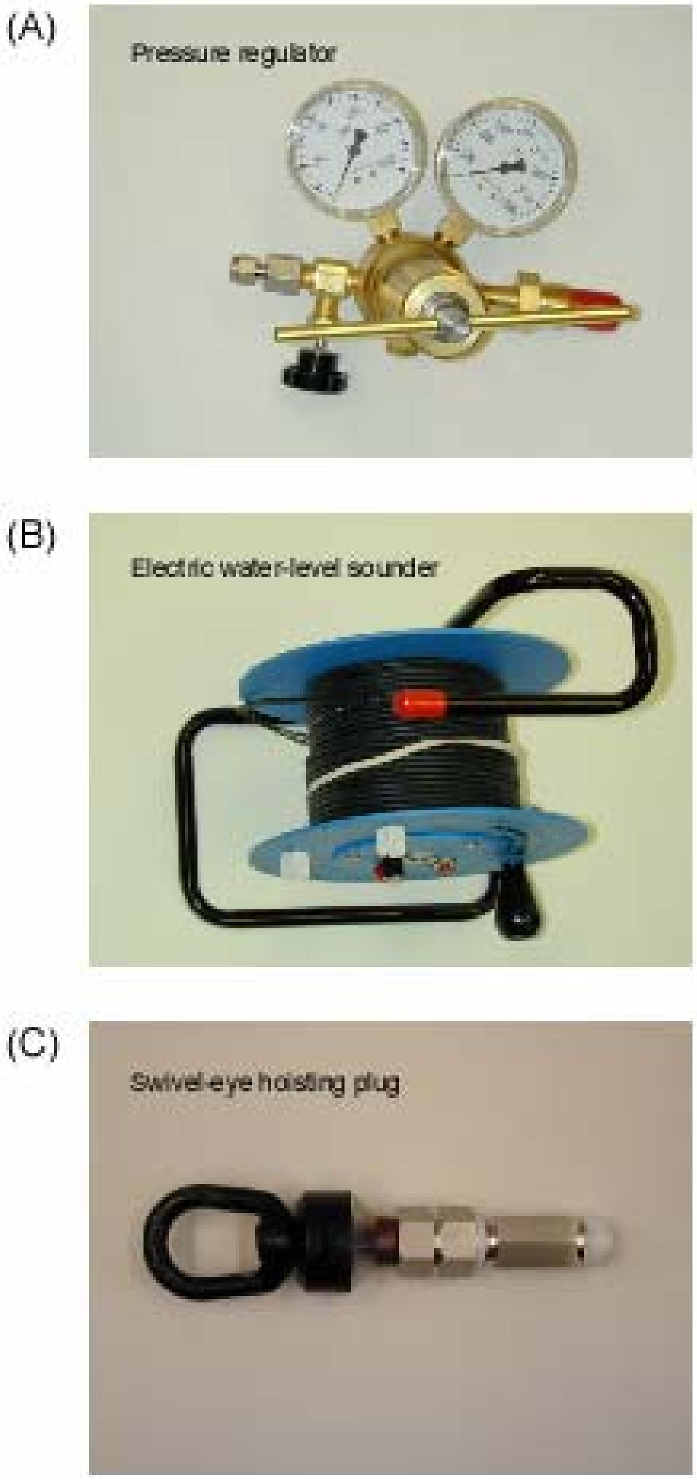

Figure 39. Photographs of (A) the pressure regulator for cylinders of compressed gas, (B) electric water-level sounder, and (C) a swivel-eye hoisting plug.

6.1 Pressure Tank Regulator

An Air Products E11-N115G High-Volume Single-Stage pressure regulator is shipped with the Multifunction BAT^3 for use on cylinders of compressed air or nitrogen. This regulator supports a maximum inlet pressure of 3,000 psi and maximum outlet pressure of 500 psi. A discussion of the pressures applied to the various downhole components of the Multifunction BAT^3 is given in sections “4.2.2 Middle- and Bottom-Zone Transducers” on page 21, “4.5 Fluid-Injection Apparatus” on page 27, “9.7 Inflating Packers to Initiate a Test” on page 89, and “9.8 Deflating Packers to End a Test” on page 91.

6.2 Electric Water-Level Indicator

A Slope Indicator electric water-level indicator is included in the equipment shipped with the Multifunction BAT^3. The water-level indicator has 150 ft of cable with increments of 0.01 ft, and it is operated by three (3) AA-size internal batteries. The water-level indicator provides a means of taking manual measurements of depth to water in the borehole (below a given datum, such as the top of the borehole casing). Manual measurements of depth to water are used to calibrate pressure transducers (see the section “9.5 Field Calibration of Pressure Transducers” on page 87).

6.3 Swivel-Eye Hoisting Plug

A swivel-eye hoisting plug is supplied with the borehole testing apparatus. The hoisting plug has a 1-inch male NPT fitting to attach to the 1-inch female NPT fitting at the top of the transducer apparatus. The hoisting plug is used if the downhole equipment is to be lowered in the borehole with a cable and winch.

7. Information and Equipment Supplied by the User

The configuration of the Multifunction BAT^3 described in this report comes equipped with most of the essentials needed to conduct hydraulic testing and geochemical sampling in 6-inch-diameter boreholes. There are, however, information and equipment that need to be supplied on site by the user in order to deploy the Multifunction BAT^3 in boreholes and insure the safe operation of this equipment.

7.1 Borehole Geophysical Logs

Using borehole packers in bedrock boreholes requires information on borehole conditions, in particular, the borehole roughness and the location of fractures. The drilling of bedrock boreholes may result in enlarged areas of the borehole either at fractures or at positions where the local stress distribution causes spalling of the rock on the borehole walls. If the packer bladder is located adjacent to an enlarged section of the borehole, the bladder may rupture as it inflates. In general, the packers used on the Multifunction BAT^3 are suited for making hydraulic seals against relatively smooth borehole walls that are approximately 6 inches in diameter.

Geophysical logging is needed prior to deploying the Multifunction BAT^3 in bedrock boreholes. In particular, a caliper log of the borehole walls is needed to assess changes in the borehole diameter. An example of a caliper log conducted in a borehole drilled in dolomite is given in figure 40, where the peaks on the caliper log are representative of bedding plane partings in the rock. The diameter of the borehole at these locations is significantly larger than 6 inches. Placing a packer on one of these features in the borehole and inflating it would most likely result in the packer bladder rupturing during inflation, as the bladder expands to seal against the borehole wall.

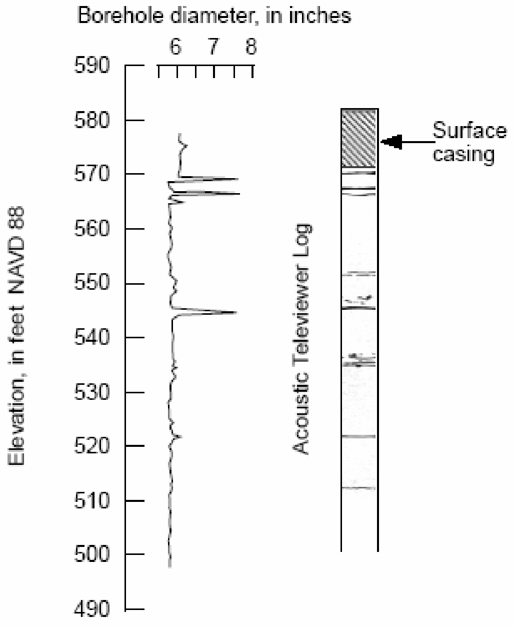

Figure 40. Diagram of a caliper log and the interpretation of an acoustic televiewer log of a borehole in dolomite near Argonne, Illinois.

An acoustic televiewer log of the borehole walls, or some of other borehole-wall scanning log, such as an analog or digital borehole camera (Williams and Johnson, 2000), is also needed prior to using the Multifunction BAT^3 in a borehole. Figure 40 shows the interpretation of an acoustic televiewer log for a borehole drilled in dolomite. The data from borehole scanning can be interpreted to identify the location of fractures intersecting the borehole, as not all fractures intersecting the borehole can be identified from a caliper log. Choosing the locations to conduct hydraulic tests in boreholes or locations to collect water samples for geochemical sampling requires a knowledge of fracture locations.

The caliper and borehole scanning logs are used to choose the length of the test interval for hydraulic tests or collecting water samples for geochemical analyses. The length of the packer bladder for the Multifunction BAT^3 is approximately 2.3 ft. Thus, smooth sections of the borehole that are unfractured and at least 2.3 ft long need to be identified as potential locations for placing packers in the borehole. The test interval is the distance between the top and bottom packers of the downhole equipment (see fig. 9 and the section "4.8 Test-Interval Length" on page 34). In defining the length of the test interval, it is advantageous to specify a packer spacing that can be applied over the entire depth of the borehole to avoid removing the downhole components of the Multifunction BAT^3 from the borehole and adjusting the spacing between the packers. The caliper and borehole scanning logs should be inspected to see if a constant packer spacing can be applied, or if the packer spacing would need to be adjusted to collect the appropriate hydraulic and geochemical data from the borehole.

It is also advantageous to have a flowmeter log conducted in the borehole under ambient and pumped conditions prior to using the Multifunction BAT^3 (Paillet, 1996). The flowmeter log can identify the most permeable fractures intersecting the borehole. Such information is beneficial in identifying locations in which to conduct hydraulic tests and collect water samples for geochemical analyses. With a flowmeter log, locations for testing in boreholes can be targeted more easily, reducing the amount of time that needs be dedicated to downhole testing with the Multifunction BAT^3.

7.2 Electric Power

If downhole testing is to include the withdrawal of water for geochemical sampling or estimation of hydraulic properties, the electric submersible pump in the Multifunction BAT^3 will be used. The pump operates on 120 V AC power. This can be supplied from a generator if connections to a local power grid are unavailable. If only fluid-injection tests or hydraulic head measurements are to be made, 120 V AC electric power is not needed.

The data-acquisition system of the Multifunction BAT^3 operates on 12 V DC power, which are supplied by the panel of batteries included in the Multifunction BAT^3. Adapters are supplied for recharging the batteries on the battery panel from a 120 V AC power source. If only fluid-injection tests or hydraulic head measurements are to be conducted, the 12V DC batteries can be used without being connected to an AC power source; however, the batteries should be fully charged before using them in this manner.

7.3 Compressed Gas

The packers, the pressure transducer “bleed” valves, and the fluid-injection valve are operated with compressed gas administered through the pressure manifold at land surface. Also, fluid-injection testing can be conducted by applying compressed gas to the water surface of a fluid reservoir tank to simulate different injection conditions in the test interval. The pressure manifold included in the Multifunction BAT^3 distributes the compressed gas from a single source to the two packers, the transducer “bleed” valves, and the fluid-injection valve. Compressed gas can be supplied to the manifold from a cylinder of compressed air or nitrogen, or from a gasoline-operated compressor. The pressure applied from the cylinders or compressor must be sufficient to operate the equipment at the depth that they are deployed in the borehole. Information concerning the pressures that need to be applied to packers is given in the section “9.7 Inflating Packers to Initiate a Test” on page 89. The pressure needed to operate the transducer “bleed” valves is discussed in the section “4.2.2 Middle- and Bottom-Zone Transducers” on page 21, and the pressure needed to operate the fluid-injection valve is discussed in the section “4.5 Fluid-Injection Apparatus” on page 27.

Compressed gas can also be used during fluid-injection testing to place a pressure greater than atmospheric pressure on the water surface of the fluid reservoir tank. For this purpose, it is recommended that a compressor be used to supply compressed gas through the in-line pressure regulator. The in-line pressure regulator will regulate pressure from the pressure source to achieve the prescribed pressure to be applied to the water surface in the fluid reservoir tank; the excess pressure will dissipated out of the in-line regulator. If a cylinder of compressed gas is used, the pressure in the cylinder will be depleted, whereas a gasoline-powered compressor can regenerate the pressure source. The maximum pressure that needs to be applied to the water surface of the fluid reservoir for fluid-injection testing is usually less than 60 psi, which is within the range of many gasoline-powered compressors.

7.4 Winch and Cable or Steel Pipe

Because of the weight of the downhole components of the Multifunction BAT^3, they must be lowered and raised in the borehole using a winch that is free standing or mounted on a truck. If the cable on the winch is used to lower the equipment in the borehole, the length of the cable mounted on the winch should be sufficient to lower the equipment to the desired depth in the borehole; the Multifunction BAT^3 is currently configured to operate at depths up to approximately 300 ft below land surface. A swivel-eye hoisting plug with a 1-inch male NPT fitting is provided to attach to the top of the transducer shrouds. The cable used to lower the downhole equipment should be attached to this hoisting plug. A winch with a capacity in excess of 2500 pounds should be used to insure that if the equipment is stuck in the borehole, the cable is sufficient to withstand stress needed to dislodge the equipment in the borehole.

Instead of using a cable attached to the winch to lower the borehole equipment, steel pipe can also be used to lower and raise the borehole apparatus. The top of the transducer shroud has a 1-inch female NPT fitting. If 1-inch-diameter pipe is not available, pipe fittings can be used to adapt the threaded fitting on the top of the transducer shroud to the diameter of the pipe available. A well servicing truck or tripod with the equipment to raise, lower, and secure steel pipe in a borehole at a given depth would be needed for this purpose.

Lowering and raising the borehole equipment with steel pipe is the safest alternative in deploying the Multifunction BAT^3 in bedrock boreholes, and it is recommended that steel pipe be used for most applications in bedrock boreholes. In boreholes with rough walls, packers may become lodged against the borehole walls. Also, if packers are not maintained at the proper inflation pressure when raising and lowering them in the borehole, they may also become lodged in the borehole (see the section “9.9 Moving the Equipment to a New Test Interval” on page 91). Using a cable to move the equipment in the borehole only offers the opportunity to lift up on the downhole equipment to dislodge it, if it becomes stuck; whereas, when using steel pipe, the weight of the pipe can push the packers through rough sections of the borehole and a torque can be applied on the pipe in some instances to dislodge the downhole equipment.

7.5 Laptop Computer

The user must supply a laptop computer with the Windows 2000 or XP operating system, and a 9-pin serial or USB port to download digital data from the data-acquisition equipment used with the Multifunction BAT^3. The laptop computer is also used to view the transducer and flowmeter data as it is acquired during testing. The laptop computer must have at least 8 megabytes (MB) of RAM (Random Access Memory) (16 MB is recommended) and at least 10 MB of hard disk space to store the Campbell Scientific LoggerNet software, and the BAT^3 Analyzer for real-time display and interpretation of the data. Additional disk space will be needed to store digital records from pressure transducers and flowmeters during testing.

7.6 Tubing and Tubing Connections

The intended application of the borehole testing apparatus and the depths at which it will be used will dictate the type and length of the 0.25-inch- and 0.5-inch-diameter tubing used between the borehole packers and from the top packer to land surface. The tubing is not included in the Multifunction BAT^3 and must be supplied by the user.

Tubing made of nylon, Teflon, stainless steel or copper in 0.25-inch and 0.5-inch diameters can be used with the Multifunction BAT^3. Tubing with diameters other than 0.25 and 0.50 inches also can be used with the Multifunction BAT^3, such as 0.375-inch-diameter tubing; however, the user will need to supply the appropriate adapting fittings to attach this tubing to the various uphole and downhole components of the Multifunction BAT^3. Different types of tubing can be used for different purposes. For example, 0.25-inch-diameter tubing used to inflate the packers can be of one type, whereas the 0.5-inch-diameter tubing for water leading from the pump can be of another type. The choice of the type of tubing will depend on the intended application of the equipment. Flexible tubing, such as nylon or Teflon tubing, however, is easier to use than copper or stainless-steel tubing when lowering and raising the apparatus in the borehole.

The current configuration of the pump apparatus has a 300 ft pump cable, which limits the depth at which the downhole equipment can be used. Table 7 itemizes the lengths of 0.25-inch- and 0.5-inch-diameter tubing that would be required for an assumed maximum depth at which the equipment is to be used in the borehole. Table 7 only gives the lengths of the tubing that would be needed from the top of the downhole equipment to land surface; additional tubing will be needed to make connections between the downhole components (see the section “4.9 Connecting Tubing” on page 35). The length of the additional tubing will depend on the length of the test interval.

In addition to supplying the tubing, the user will need to supply fittings capable of connecting tubing together. Swagelok fittings for 0.25-inch and 0.50-inch-diameter tubing have been used in the design of the downhole components and the downhole-control equipment of the Multifunction BAT^3, and it is recommended that tubing connections be made with similar Swagelok fittings to maintain uniformity. In particular, the user will need to supply 0.25-inch-union (SS-400-6) and 0.50-inch-union (SS-810-6) Swagelok fittings. Other types of Swagelok fittings may also be needed to adapt the fittings on a user-supplied fluid reservoir tank to 0.25- and 0.50-inch-diameter tubing. Wrenches capable of tightening Swagelok fittings of various dimension also will have to be supplied by the user.

Table 7. Length of 0.25-inch- and 0.50-inch-diameter tubing the user must supply for operating the downhole components of the Multifunction BAT3 for different configurations of the downhole equipment.

[See section “5.7 Summary of Connections to Data-Acquisition and Downhole-Control Equipment” on page 58 for additional information; D_{max} is the maximum depth in the borehole at which the equipment is to be used. The lengths are for tubing connections from the top of the downhole components to land surface. Additional 0.25-inch- and 0.50-inch-diameter tubing will also be needed for connections between the downhole components in the test interval; the length of this tubing will depend on the length of the test interval.]

Tubing Diameter in inches	Fluid-Withdrawal and Fluid-Injection Testing	Fluid-Withdrawal Testing	Fluid-Injection Testing
0.25	$4\ D_{max}$	$3\ D_{max}$	$4\ D_{max}$
0.50	$2\ D_{max}$	$1\ D_{max}$	$1\ D_{max}$

7.7 Fluid Reservoir Tank

If fluid is to be injected from land surface for fluid-injection tests or as a part of tracer tests, a fluid reservoir of sufficient volume will need to be supplied by the user. Figure 41 shows an example of a fluid reservoir tank. The fluid reservoir will need to have an outlet at the base of the tank that can be a adapted to 0.5-inch-diameter tubing used in the injection apparatus. The tank should also have a manually operated valve at the outlet of the tank to retain fluid in the tank when tubing is not connected to the outlet. It is also recommended that a filter be placed at the outlet of the fluid reservoir tank to remove particulate material that may have settled in the tank. Removing particulate material from the water that is to be injected into the borehole reduces the possibility that the flowmeters will become clogged during their operation. An example of a filter that can be placed at the outlet of the fluid reservoir tank is shown in figure 42. Filters similar to the one shown in figure 42 are commonly available at vendors selling plumbing supplies.

In fluid-injection tests or fluid injection during tracer tests, the valve at the tank outlet is opened and the fluid injection is controlled by operating the downhole fluid-injection valve with compressed gas. The fluid in the reservoir is at a higher hydraulic head than in the test interval in the borehole, and thus, opening the downhole injection valve will result in water entering the test interval.

An alternative approach to fluid injection is to conduct the fluid injection by applying an air pressure greater than atmospheric pressure to the water surface in the fluid reservoir tank. This may be advantageous in speeding the delivering of water to the test interval, as may be needed in conducting a tracer test, or to estimate the hydraulic properties of the test interval under different injection rates. If a pressure greater than atmospheric pressure is to be applied to the water surface in the fluid reservoir, then the reservoir will need to have pressure-tight fittings above the water surface in the fluid reservoir tank from which pressure can be applied (fig. 41). An in-line pressure regulator is supplied to regulate the air pressure applied to the water surface of the fluid reservoir tank for this purpose (see the section “5.2 In-Line Pressure Regulator” on page 44).

The injection tank shown in figure 41 has a gate valve extending from the bottom of the tank that is adapted to a Swagelok fitting that connects to 0.5-inch-diameter tubing. A transparent tube with pressure-tight fittings is attached along the axis of the tank, so that the water level in the tank can be viewed; if the tank is transparent, this method of viewing the water level is not necessary. Two pressure-tight fittings are at the top of the tank. When filling the tank with water, the outlet at the bottom of the tank is closed, one fitting on the top of the tank is used as a water inlet, and the other fitting is left open to allow air to escape. When operating the tank during fluid-injection testing, one fitting at the top of the tank is used as a source of compressed air to pressurize the water surface and the other fitting on the top of the tank is closed with a pressure-tight fitting.

If the fluid reservoir tank is to be pressurized during fluid injection, the tank should be composed of materials that will not deform during this procedure. Usually, pressures less than 60 psi above atmospheric pressure are applied to the water surface of the fluid reservoir tank during fluid-injection testing. In choosing a fluid reservoir tank, the user should be concerned with the safe operation of that tank under the pressures that will be applied during fluid-injection testing.

Figure 41. Photograph of a fluid reservoir tank used for fluid-injection testing.

Figure 42. Photograph of an in-line filter used at the outlet of the fluid reservoir tank to remove particulate material from the injection fluid.

After filling the fluid reservoir with water, a tube is used to connect one of the fittings at the top of the tank with the in-line pressure regulator (fig. 29), which in turn is connected to a source of compressed gas. The outlet of the fluid reservoir tank is connect to 0.5-inch-diameter tubing extending from the three-way valve on the plate with the Flowmeters 1 and 2, which are used to monitor fluid-injection rates. The procedure to remove air from the 0.5-inch-diameter fluid-injection tubing is discussed in the section "9.3 Preparing the Fluid Reservoir Tank for Fluid Injection" on page 83. Air must be removed from the injection tubing to avoid injecting air into the test interval; injecting air in the test interval could result in erroneous estimates of hydraulic properties of the test interval, or may alter the ground-water chemistry.

7.8 Extension Pipe

The length of the test interval can be varied, depending on borehole conditions. A 1-inch-diameter extension pipe of the desired length with NPT threads would need to be provided by the user to increase the length of the test interval from minimum test interval lengths described in the section "4.8 Test-Interval Length" on page 34. A spare union ball fitting is shipped in Box 1 of the Multifunction BAT^3. The two pieces of the union ball fitting are attached to the ends of the 1-inch-diameter pipe and connect to the bottom packer and either the pump apparatus or the fluid-injection apparatus.

7.9 Geochemical Sampling Equipment

If the Multifunction BAT^3 is used to withdraw water from the test interval for the purpose of collecting water samples for geochemical analyses, it is assumed that the uphole equipment needed to collect and preserve the water samples will be provided on site. A flow-through cell used in geochemical sampling to monitoring geochemical field parameters, such as temperature, pH and specific conductance, can be placed either after the flowmeter measuring the pump discharge, or in the fluid discharge tube before the flowmeter. Water samples should be collected from the tubing leading from the pump after the flowmeter to insure that an accurate measure of the flow rate is collected; collecting water samples for geochemical analyses prior to the flowmeter will result in loss of water to the flowmeter and an inaccurate measurement of the pumping rate.

7.10 Decontamination Procedures and Equipment

If the ground water is suspected of having contaminants, which adversely affect the ground-water quality, the user of the Multifunction BAT^3 should develop decontamination procedures and have decontamination equipment available. The downhole components of the Multifunction BAT^3 including the transducer and pump cables should be subject to decontamination after it has come in contact with the contaminated ground water and prior to repacking the equipment in its shipping boxes. In addition, the pump apparatus should be decontaminated and purged so that future water samples do not show detections of ground-water contaminants.

In some site investigations, procedures for collecting water samples for geochemical analyses and conducting hydraulic tests in boreholes may first entail the decontamination of the downhole components of the Multifunction BAT^3 prior to deploying it in a borehole. In such cases, the decontamination procedures will need to be applied to the tubing supplied by the user, as well as the downhole components and transducer and pump cables. If multiple boreholes are to be tested, the user will need to decide if tubing should be discarded or transferred from borehole to borehole after being subject to decontamination. The hoisting apparatus used to raise or lower the downhole components of the Multifunction BAT^3 that is in contact with the ground water may also require decontamination.

The procedures, equipment, and supplies needed for decontamination of the borehole equipment will depend on the particular ground-water contaminant. A complete discussion of protocols for decontamination of borehole equipment is beyond the scope of this report. The user should refer to documents on decontamination, such as ASTM (1990), US EPA (1994, 2001), and Wilde (2004) for more information on equipment and procedures for decontaminating equipment in contact with contaminated ground water.

8. Data Acquisition and Visualization

The data-acquisition equipment of the Multifunction BAT^3 uses a Campbell Scientific CR23X Data Logger that is programmed to monitor pressure transducers and flow meters. Digital data stored on the data logger is retrieved by a laptop computer. To access the data logger from a laptop computer, a license for a single copy of the Campbell Scientific LoggerNet software for data acquisition has been procured. The installation CD is forwarded to the user with the borehole equipment. At the completion of testing using the borehole equipment described in this report, the user must remove this software from the laptop computer used for data acquisition. A program to operate the Campbell Scientific CR23X Data Logger for the equipment described in this report has been prepared and can be forwarded to the user electronically.

The Campbell CR23X Data Logger is wired on the data-acquisition panel to monitor a barometric pressure sensor, three pressure transducers, and two flow meters. A data-acquisition program for the data logger has been written explicitly for the acquisition of data from these sensors. The data logger acquires the data from the sensors at a predetermined interval and stores the data internally. This data is then downloaded to a laptop computer while the data are being collected. It is recommended that a laptop computer be used during the data collection, so that the data stored in the data logger can be downloaded to a file on the laptop computer. The data logger has a large, but finite memory to store data records. Once the storage capacity of the data logger has been reached, the earliest data records on the data logger will be over written by the most recently collected data. Details about the storage capacity of the Campbell Scientific CR23X Data Logger are available from Campbell Scientific product literature.

A laptop computer is also recommended for data acquisition so that data can be viewed as it is being collected to insure that the testing is being conducted properly, and to make decisions on the operation of the test. The BAT^3 Analyzer was developed to serve as a software interface to view the data as it is collected by the data logger and downloaded to the laptop computer (Winston and Shapiro, 2007).

The data-acquisition program that has been written for the sensors attached to the data-acquisition panel has been written to record the “raw” data responses from the various sensors. For example, the millivolt responses from the barometric pressure sensor and the pressure transducers, and the frequency of the flow meters in Hertz (Hz) are recorded and stored by the data logger and downloaded to a file on the laptop computer. Calibrations for these sensors, relating millivolt responses to pressure, and the flow meter turbine frequency to a flow rate are not programmed into the data-acquisition program on the data logger. Calibrations of these sensors could be subject to change, and therefore, the “raw” data is recorded and stored in a separate file. Interpretation of this raw data and the application of the calibrations for the sensors can be applied using the BAT^3 Analyzer. During the collection of the data, the data can be visualized using assumed or factory calibrations for the purpose of visualizing the data as it is collected. The "raw" data file can also be revisited if updated calibrations are provided, or if field calibration of the sensors is conducted to update the factory or laboratory calibrations. A discussion of field calibrations of the pressure transducers is discussed in the section "9.5 Field Calibration of Pressure Transducers" on page 87. Additional information about the application of sensor calibrations to raw data and the operation of the BAT^3 Analyzer is given in Winston and Shapiro (2007).

8.1 Connecting the Laptop Computer to the Data Logger

Prior to connecting the laptop computer to the Campbell Scientific CR23X Data Logger, the Campbell Scientific LoggerNet software must be loaded on the laptop computer. Instructions for loading this software are listed on the installation CD that is supplied with the Multifunction BAT^3.

The laptop computer is connected to the data logger through the 9-pin serial or USB port on the computer and the 9-pin optically isolated interface on the Campbell Scientific CR23X Data Logger. The appropriate cable for this connection is supplied with the Multifunction BAT^3 and is shipped in Box 5.

To open communication between the laptop computer and the Campbell Scientific CR23X Data Logger, the Campbell Scientific LoggerNet software is used. The steps for initiating the communication between the laptop computer and the Campbell Scientific CR23X Data Logger are provided in the product literature for the Campbell Scientific LoggerNet Software. A summary of these steps is given below.

6. With the computer operating, connect the serial or USB port of the laptop computer to the optically isolated interface on the Campbell Scientific CR23X Data Logger.
7. Start the Campbell Scientific LoggerNet software by double clicking on the program icon that appears on the desktop; this operation will open buttons that control the operations within the Campbell Scientific LoggerNet software.
8. Click on the **Setup** button that appears on the software panel. The **Setup** window will appear.
9. If a communications port (ComPort) is not listed on the left hand side of the **Setup** window, click on the **Add Root** button at the top of the **Setup** window to add a communications port. This action will list **ComPort_1** on the left-hand side of the **Setup** window.
10. The user will need to make sure that **ComPort_1** points to the correct communication device on the laptop computer, for example, a 9-pin serial port or a USB port. Click on **ComPort_1** to highlight it on the left-hand side of the **Setup** window and then select the correct **Com Port Connection** from the pull-down menu on the right-hand side of the **Setup** window. The user may need to refer to the **System Properties** window on the laptop computer to list the active communications port. For example, on the **Windows XP** operating system, the **Device Manager** under the **Hardware** tab of the **System Properties** window will show a list of operating **Ports**. The user should refer to the operating system information to identify the operational ports on the laptop computer.
11. With **ComPort_1** highlighted, click on the **Add** button on the top of the **Setup** window. This action will open the **Add Device** window.

12. Click on **CR23X** on the left-hand side of the **Add Device** window and then click on the **Add Now** button to add the CR23X Data Logger to **ComPort_1**; **ComPort_1** should also be highlighted on the right-hand side of the **Add Device** window.
13. The **Add Device** window can then be closed by clicking on the **Close** button, and **CR23X** should then appear under **ComPort_1** on the left-hand side of the **Setup** window.
14. Click on **CR23X** to highlight it under **ComPort_1** on the left-hand side of the **Setup** window. A series of tabs will appear on the right-hand side of the **Setup** window.
15. Click on the **Hardware** tab, and check the **Communications Enabled** check box.
16. Click on the **Schedule** tab, and check the **Scheduled Collection Enabled** check box.
17. Under the **Schedule** tab, change the **Collection Interval** to 15 seconds, or a suitable collection interval for the type of testing that is being conducted. The default values for the other information on the **Schedule** tab can remain unchanged. With this choice of the **Collection Interval**, the Campbell Scientific CR23X Data Logger will be queried by the computer every 15 seconds and the new data recorded by the data logger will be appended to the end of a data file on the laptop computer. The BAT^3 Analyzer will look at this data file on the laptop computer for real-time data visualization. If this data file has not been updated, then the BAT^3 Analyzer will not update the graphs and digital information that it displays. A different **Collection Interval** can also be set in this dialog. For example, a **Collection Interval** greater than 15 seconds can be specified if a hydraulic test of several hours is being conducted and it is not necessary to view changes in data as frequently as in hydraulic tests conducted over minutes or tens of minutes
18. Click on the **Final Storage Area 1** tab, and check the **Enabled For Collection** check box.
19. Under the **Final Storage Area 1** tab, select an **Output File Name** by either typing the path name into the dialog box or browsing to open the **Save As** window to select the location and filename where data from the data logger is to be saved. The filename should have the “dat” file extension. The default values for the other information on the **Final Storage Area 1** tab can remain unchanged.
20. At the bottom of the Setup window click on the **Apply** button, and then close the **Setup** window by clicking the close button on the upper right-hand side of the window.
21. Click on the **Connect** button on the LoggerNet panel. This opens the **Connect Screen** window. Under **Stations** on this window, **CR23X** should be highlighted and then the **Connect** button should be clicked. This will connect the laptop computer to the data logger, and data from the data logger will be downloaded to the file that was specified above.
22. If the connection is successful, click on the **Set Station Clock** button to set the clock on the data logger using the clock on the laptop computer. The clock time on the laptop computer should also be used in conducting various operations of the downhole equipment during the hydraulic testing or geochemical sampling so that responses of the sensors attached to the data logger coincide with operations of the downhole components.
23. The Campbell Scientific LoggerNet software is left operating during testing with the Multifunction BAT^3.

By completing the instructions given above, the laptop computer is connected to and communicating with the Campbell Scientific CR23X Data Logger. If the data logger is operating, responses from the barometric pressure sensor, pressure transducers, and flow meters are collected at a prescribed sampling interval. The specification of the sampling interval is discussed in the sections “8.3 Loading a Data-Acquisition Program” on page 73 and “8.4 Changing the Sampling Interval” on page 74. The instructions given above instruct the laptop computer to communicate with the data logger and download data to the file specified on the laptop computer at the specified **Collection Interval**.

8.2 Terminating the Connection to the Data Logger

While the hydraulic testing or geochemical sampling is being conducted using the Multifunction BAT^3, communication is maintained between the laptop computer and the Campbell Scientific CR23X Data Logger. The Campbell Scientific LoggerNet software operates with the connection established between the laptop computer and the data logger. After all testing has been completed in the borehole by the Multifunction BAT^3, the communication between the laptop computer and the data logger can be terminated by clicking the **Disconnect** button on the **Connect Screen** window. This terminates the connection and the Campbell Scientific LoggerNet software can be closed by clicking the **Close** button on the top right-hand side of the LoggerNet panel. Additional information about establishing connections between a laptop computer and the data logger can be found in Campbell Scientific product literature for the LoggerNet software and the CR23X Data Logger.

8.3 Loading a Data-Acquisition Program

Instructions for sampling the sensors that are wired to the Campbell Scientific CR23X Data Logger and used by the Multifunction BAT^3 need to be downloaded to the data logger prior to the start of testing in a borehole. The instructions to query the sensors of the Multifunction BAT^3, including the time interval at which the sensors are sampled, are referred to as a data-acquisition or data-logger program. A data-logger program has been prepared for the sensors wired to the Campbell Scientific CR23X data logger. This program can be forwarded to the user electronically.

In the following instructions for loading a data-acquisition program on the Campbell Scientific CR23X Data Logger, it is assumed that the data logger program has been compiled and it is stored on the laptop computer. It is also assumed that communications have been successfully established between the laptop computer and the data logger (see the section “8.1 Connecting the Laptop Computer to the Data Logger” on page 71). Under these assumptions, the following steps are taken to load a data-logger program on the Campbell Scientific CR23X Data Logger:

1. It is assumed that the data logger program is stored under the folder C:\BAT3\Data_Logger\CR23X\.
2. On the **Connection Screen** window, under the **Program** area click **Send**, and then navigate on the **Send Program to Station** window to the folder containing the data logger program for the Campbell Scientific CR23X.
3. It is assumed that the program name is BAT3_23X.DLD in the folder C:\BAT3\Data_Logger\CR23X\. Select this program and click the **Open** button on the **Send Program to Station** window. Files with the “DLD” file extension are the compiled form of the data logger program.

4. Clicking the **Open** button displays a **Caution** window that warns of the potential loss of data. Click the **OK** button on the **Caution** window to continue. If the program is properly received by the data logger, a dialog box stating a successful transmission is displayed. Click **OK** to continue.

The data-logger program that has been prepared for the Multifunction BAT^3 is shown in figure 43. In this program a sampling interval of 30 seconds has been applied, which means the sensors (barometer, transducers and flow meters) are queried every 30 seconds by the data logger, and the data from the sensors are then stored internally in the data logger. The sampling interval associated with the data logger program does not have to be the same as the Collection Interval at which the laptop computer communicates with the data logger and retrieves any new data stored on the data logger (see the section "8.1 Connecting the Laptop Computer to the Data Logger" on page 71).

8.4 Changing the Sampling Interval

The sampling interval in the data-logger program defines the frequency at which the sensors attached to the data logger are sampled and the data are stored internally to the data logger. In some instances the sampling interval for the data logger program may not be suitable to capture the hydraulic behavior that is induced with either pumping or fluid injection. To change the sampling interval, the data-logger program must be modified. To modify the sampling interval, a single value in the data logger program must be changed. The following instructions should be followed to change the sampling interval in the data-logger program:

1. If the Campbell Scientific LoggerNet software is not running, start the Campbell Scientific LoggerNet software by double clicking the program icon that appears on the desktop of the computer.
2. Click the **Edlog** button on the LoggerNet panel. An Edlog window appears; Edlog is the programming interface for data-logger programs in the LoggerNet software.
3. Under the **File** menu choose **Open** and in the dialog box that appears, search for the program BAT3_23X.CSI. It is assumed that the file is located in the folder C:\BAT3\Data_Logger\CR23X\. Highlight the file and click **Open** to open the file. If the data-logger program has been copied to another path on the laptop computer, the appropriate path should be searched and the appropriate file should be opened.
4. To change the sampling interval, click on the integer number in the line "**Execution Interval (Seconds)**" (see fig. 43). In the example given in figure 43, the execution interval is **30** seconds. Moving the pointer and clicking on this number will result in a gray box overlaying the number. The new sampling interval (in seconds) can then be typed to replace the previous sampling interval.
5. Under the **File** menu, choose **Save As**, and in the dialog box that appears, rename the data logger program so that the original file is not over-written, for example, BAT3_23A.CSI. The CSI file extension will be added to the filename that the user specifies.
6. Click the **Save** button and a dialog asking to compile the program appears. Click **Yes** to compile the program.
7. If there are no errors resulting from the change in the execution interval, the **Compiling** window should show "**No errors detected**".

8. Click **OK** to close the **Compiling** window.
9. Under the **File** menu choose **Exit** to end the editing session of the data-logger program.

Additional information on editing data-logger programs can be found in the Campbell Scientific product literature for the LoggerNet software.

The newly edited data-logger program with the new sampling interval must be sent to the data logger to operate on the sensors at the new sampling interval. The section "8.3 Loading a Data-Acquisition Program" on page 73 gives the instructions on how to load a data-logger program after establishing a communication between the laptop computer and the Campbell Scientific CR23X Data Logger.

8.5 Raw Data Files

An example of a "raw" data file collected from the Campbell Scientific CR23X Data Logger during testing using the Multifunction BAT^3 is shown in figure 44. The "raw" data file contains the sensor output without alteration from calibrations that convert the sensor output to physically meaningful values. Each row in the data file contains the sensor values at a specific time. The values are separated by commas, and each value is assumed to occupy a column. For example, the first value in each row is assumed to occupy Column 1, the second value is assumed to occupy Column 2, and so forth. In each row of the "raw" data file there are 12 values. The values in each row of the data in the "raw" data files have the following meaning:

Column 1: Data Logger ID
Column 2: Year
Column 3: Julian Day
Column 4: HrMin (24 hour clock)
Column 5: Seconds
Column 6: Panel Temperature (degrees Celsius)
Column 7: Millivolt response - barometer
Column 8: Millivolt response - upper transducer
Column 9: Millivolt response - middle transducer
Column 10: Millivolt response - bottom transducer
Column 11: Frequency (Hz) response - Flow Meter A or Flow Meter 1
Column 12: Frequency (Hz) response - Flow Meter 2

The panel temperature recorded in Column 6 of the "raw" data is the temperature on the data logger panel. The panel temperature is recorded from a sensor internal to the data logger. The measured responses listed in columns 7 through 12 of the "raw" data have been described previously.

The data structure noted above is used, regardless of whether pumping or fluid injection is being conducted. If pumping is being conducted, then only one flow meter will be used. If fluid-injection testing is being conducted, two flow meters may be used, depending on the hydrogeologic conditions.

```
;{CR23X}
;
*Table 1 Program
  01: 30        Execution Interval (seconds)
; Data Logger Panel Temperature
1:  Panel Temperature (P17)
 1: 1        Loc [ Temp_C    ]
;Barometric Pressure Sensor
2:  Excite-Delay (SE) (P4)
 1: 1        Reps
 2: 15       5000 mV, Fast Range
 3: 1        SE Channel
 4: 1        Excite all reps w/Exchan 1
 5: 100      Delay (units 0.01 sec)
 6: 5000     mV Excitation
 7: 2        Loc [ Barometer ]
 8: 1.0      Mult
 9: 0.0      Offset
;Upper Zone Pressure Transducer
3:  Full Bridge w/mv Excit (P9)
 1: 1        Reps
 2: 15       5000 mV, Fast, Ex Range
 3: 12       50 mV, Fast, Br Range
 4: 3        DIFF Channel
 5: 2        Excite all reps w/Exchan 2
 6: 5000     mV Excitation
 7: 3        Loc [ mv_V_Up   ]
 8: 1.0      Mult
 9: 0.0      Offset
;Middle Zone Pressure Transducer
4:  Full Bridge w/mv Excit (P9)
 1: 1        Reps
 2: 15       5000 mV, Fast, Ex Range
 3: 12       50 mV, Fast, Br Range
 4: 5        DIFF Channel
 5: 3        Excite all reps w/Exchan 3
 6: 5000     mV Excitation
 7: 4        Loc [ mv_V_Mid  ]
 8: 1.0      Mult
 9: 0.0      Offset
;Bottom Zone Pressure Transducer
5:  Full Bridge w/mv Excit (P9)
 1: 1        Reps
 2: 15       5000 mV, Fast, Ex Range
 3: 12       50 mV, Fast, Br Range
 4: 7        DIFF Channel
 5: 4        Excite all reps w/Exchan 4
 6: 5000     mV Excitation
 7: 5        Loc [ mv_V_Low  ]
 8: 1.0      Mult
 9: 0.0      Offset
; Flow Meter A or Flow Meter 1
6:  Pulse (P3)
 1: 1        Reps
 2: 1        Pulse Channel 1
 3: 1        Low Level AC, All Counts
 4: 6        Loc [ Hz_FM_1_A ]
 5: .033333  Mult
 6: 0.0      Offset
;Flow Meter 2
7:  Pulse (P3)
 1: 1        Reps
 2: 2        Pulse Channel 2
 3: 1        Low Level AC, All Counts
 4: 7        Loc [ Hz_FM_2   ]
 5: .033333  Mult
 6: 0.0      Offset
8:  Do (P86)
 1: 10       Set Output Flag High (Flag 0)
9:  Resolution (P78)
 1: 1        High Resolution
10:  Real Time (P77)^11218
 1: 1221     Year,Day,Hour/Minute,Seconds (midnight = 2400)
11:  Sample (P70)^6662
 1: 7        Reps
 2: 1        Loc [ Temp_C    ]
```

Figure 43. Listing of a data-acquisition program for monitoring sensors attached to the Campbell Scientific CR23X Data Logger used with the Multifunction BAT^3.

```
108,2001,339,1146,31,27.48,2260,2.9164,1.4466,1.4282,0,0
108,2001,339,1147,.99999,27.429,2260.3,2.9162,1.4468,1.428,0,0
108,2001,339,1147,31,27.369,2259.6,2.916,1.4462,1.4285,0,0
108,2001,339,1148,.99999,27.288,2259.6,2.9164,1.4473,1.4285,0,0
108,2001,339,1148,31,27.207,2259.6,2.9167,1.4466,1.4283,0,.03333
108,2001,339,1149,.99999,27.117,2259.9,2.9162,1.4477,1.4282,0,.3
108,2001,339,1149,31,27.021,2259.9,2.9162,1.4452,1.4281,0,.66666
108,2001,339,1150,.99999,26.927,2259.5,2.9161,1.4472,1.4286,13.067,17.866
108,2001,339,1150,31,26.839,2259.5,2.9158,1.4452,1.4286,11.067,13.667
108,2001,339,1151,.99999,26.743,2259.1,2.9161,1.4467,1.4289,46.433,59.866
108,2001,339,1151,31,26.656,2259.1,2.9158,1.4456,1.4286,.2,.06667
108,2001,339,1152,.99999,26.577,2259.1,2.9157,1.4474,1.4285,0,0
108,2001,339,1152,31,26.495,2259.4,2.9155,1.4459,1.4294,0,.06667
108,2001,339,1153,.99999,26.423,2259.1,2.9158,1.4455,1.4288,.59999,3.2666
108,2001,339,1153,31,26.365,2259.1,2.9157,1.447,1.4291,6.5666,16.866
108,2001,339,1154,.99999,26.307,2259.1,2.9155,1.4465,1.4294,40.9,59.499
108,2001,339,1154,31,26.25,2259.1,2.9153,1.6372,1.6543,8.0333,16.3
108,2001,339,1155,.99999,26.207,2259.1,2.9153,1.6425,1.6623,.23333,2.5333
108,2001,339,1155,31,26.177,2258.8,2.9155,1.6214,1.645,0,.79999
108,2001,339,1156,.99999,26.141,2259.1,2.9151,1.6132,1.6323,0,.53333
108,2001,339,1156,31,26.128,2259.1,2.9156,1.599,1.6217,.16666,3.4
108,2001,339,1157,.99999,26.113,2258.8,2.9152,1.8614,1.8821,5.2999,11.267
108,2001,339,1157,31,26.128,2258.8,2.915,2.0121,2.0332,.53333,2.9666
108,2001,339,1158,.99999,26.156,2258.8,2.9212,2.008,2.0283,0,.03333
108,2001,339,1158,31,26.207,2259.1,2.921,2.0034,2.0238,0,0
108,2001,339,1159,.99999,26.265,2258.8,2.9212,2.0003,2.0194,0,.03333
108,2001,339,1159,31,26.337,2258.8,2.9219,1.9966,2.0161,0,.03333
108,2001,339,1200,.99999,26.416,2258.8,2.9225,1.9917,2.0119,0,0
108,2001,339,1200,31,26.502,2258.8,2.9232,1.9882,2.0085,0,0
108,2001,339,1201,.99999,26.589,2258.8,2.9232,1.9849,2.0053,0,0
108,2001,339,1201,31,26.692,2258.8,2.9242,1.9825,2.0023,0,.03333
108,2001,339,1202,.99999,26.788,2258.8,2.9242,1.9786,1.9993,0,0
108,2001,339,1202,31,26.882,2258.8,3.0837,1.9764,1.9967,0,.26666
108,2001,339,1203,.99999,26.978,2258.8,2.9263,1.9722,1.9932,0,.43333
108,2001,339,1203,31,27.074,2258.8,3.3746,1.9719,1.9913,0,0
108,2001,339,1204,.99999,27.162,2258.8,3.369,1.968,1.9888,0,0
108,2001,339,1204,31,27.252,2258.8,3.4471,1.9653,1.9856,0,0
108,2001,339,1205,.99999,27.354,2258.7,3.4422,1.9629,1.9836,0,0
108,2001,339,1205,31,27.465,2258.7,3.437,1.9598,1.9816,0,0
108,2001,339,1206,.99999,27.57,2258.7,3.4318,1.9591,1.9796,0,0
108,2001,339,1206,31,27.683,2258.7,3.4277,1.9554,1.9765,0,0
108,2001,339,1207,.99999,27.788,2258.7,3.4231,1.953,1.9745,0,0
108,2001,339,1207,31,27.893,2258.7,3.5228,2.0033,2.0233,0,0
108,2001,339,1208,.99999,27.991,2258.4,3.5257,1.9947,2.0237,0,0
108,2001,339,1208,31,28.074,2258.6,3.5241,1.991,2.0227,.53333,2.4
108,2001,339,1209,.99999,28.158,2259,3.5208,1.9879,2.0215,0,0
108,2001,339,1209,31,28.235,2258.6,3.518,1.983,2.0194,0,0
108,2001,339,1210,.99999,28.318,2258.6,3.5149,1.9841,2.0187,0,0
108,2001,339,1210,31,28.403,2258.6,3.5117,1.9814,2.0164,0,0
108,2001,339,1211,.99999,28.487,2258.9,3.5084,1.9811,2.0154,0,0
108,2001,339,1211,31,28.57,2258.2,3.5052,1.9794,2.0137,0,0
108,2001,339,1212,.99999,28.664,2258.5,3.5025,1.9774,2.0125,0,0
108,2001,339,1212,31,28.756,2258.5,3.4988,1.9742,2.0103,0,0
108,2001,339,1213,.99999,28.841,2258.1,3.4963,1.9742,2.0093,0,0
108,2001,339,1213,31,28.942,2258.5,3.4929,1.9723,2.0075,0,0
108,2001,339,1214,.99999,29.027,2258.5,3.49,1.9702,2.0059,0,0
108,2001,339,1214,31,29.121,2258.4,3.4868,1.9696,2.0042,0,0
108,2001,339,1215,.99999,29.222,2258.4,3.4835,1.9686,2.0032,0,0
108,2001,339,1215,31,29.324,2258.4,3.4814,1.9656,2.0016,0,.49999
108,2001,339,1216,.99999,29.427,2258.4,3.4793,1.9698,2.0011,0,0
108,2001,339,1216,31,29.521,2258,3.4788,1.9663,2,0,0
108,2001,339,1217,.99999,29.617,2258,3.4762,1.9661,1.9998,0,0
108,2001,339,1217,31,29.719,2257.9,3.4737,1.9648,1.9977,0,.26666
108,2001,339,1218,.99999,29.813,2257.9,3.4709,1.9609,1.9961,0,0
```

Figure 44. Listing of a “raw” data file collected from the Campbell Scientific CR23X Data Logger used to monitor the sensors attached to the Multifunction BAT^3.

8.6 Real-Time Data Visualization

Real-time visualization of the data from the sensors of the Multifunction BAT^3 is conducted using the BAT^3 Analyzer (Winston and Shapiro, 2007), which is software developed to visualize the sensor responses in real time during testing with the Multifunction BAT^3. The BAT^3 Analyzer has the following attributes:

1. Digital records and graphical displays of the sensor responses can be shown as a function of time for all or part of the data set.
2. Calibrations can be applied to the "raw" data to display physically meaningful values.
3. Data files with calibrations applied to the "raw" data can be saved for later use and interpretation.
4. Calibrations of transducers and flow meters can be conducted from selected measurements in the raw data files when used in conjunction with corroborating check measurements.
5. Libraries of calibrations for sensors can be created, saved, and updated.
6. Combinations of sensor calibrations used to interpret transducer and flow meter records during testing can be created, saved and reloaded.
7. Interpretations of transducer responses to pumping, fluid-injection, and slug tests can be conducted using various hydrogeologic conceptual models of the formation to estimate the hydraulic properties of the test interval.
8. Graphical displays of data and model results can be saved to files or printed.

Details regarding the installation and operation of the BAT^3 Analyzer are given in Winston and Shapiro (2007). The BAT^3 Analyzer opens the data file that was created using the Campbell Scientific LoggerNet software on the laptop computer; this is the data file on the laptop computer where records from the data logger are stored. The BAT^3 Analyzer checks for updates to the data file at a specified time interval. Consequently, during data acquisition, the Campbell Scientific LoggerNet software must be operating simultaneously with the BAT^3 Analyzer on the laptop computer, and the communication between the laptop computer and the data logger must be established through the Campbell Scientific LoggerNet software (see the section "8.1 Connecting the Laptop Computer to the Data Logger" on page 71). Also, it should be noted that terminating the operation of the BAT^3 Analyzer does not affect the collection of data on the data logger, or the downloading of data from the data logger to the "raw" data file on the laptop computer. Instructions concerning the termination of the connection between the laptop computer and the data logger are given in the section "8.2 Terminating the Connection to the Data Logger" on page 73.

8.7 Documentation Collected During Borehole Testing

Although digital records are collected using the data-acquisition equipment, careful written records on the configuration, deployment, and operation of the Multifunction BAT^3 are also needed to interpret the transducer and flow meter data for the purpose of using the results of the borehole testing in calculating the hydraulic head and estimating the hydraulic properties of the test intervals.

8.7.1 Testing Conducted in Each Borehole

For the testing conducted in each borehole, the following information should be recorded:

1. Configuration and dimensions of the downhole equipment and color scheme used to label tubing and transducer cables extending downhole.

2. Dimensions of the test interval (fig. 9) and the distance from the top of the test interval to the top of the downhole equipment. These dimensions are crucial to insure the proper location of the packer bladders and that the test interval isolates selected features viewed on geophysical logs of the borehole.
3. Date and time the borehole equipment is first lowered into the borehole.
4. Filename and directory on the laptop computer where digital records are downloaded from the data-acquisition equipment (see the section "8.1 Connecting the Laptop Computer to the Data Logger" on page 71).
5. Filename of data-logger program used for data acquisition (see the section "8.3 Loading a Data-Acquisition Program" on page 73).
6. Date and time of manual water-level measurements in the borehole to perform a field calibration of the transducers (see the section "9.5 Field Calibration of Pressure Transducers" on page 87).
7. Date and time equipment is removed from the borehole.
8. Date and time that data acquisition is stopped.

8.7.2 Tests Conducted in a Test Interval

For each test conducted in an interval of the borehole, the following information should be recorded:

1. Depth of the test interval below a known datum, for example, the depth below the top of the surface casing or land surface.
2. Length of the cable or pipe that must extend downhole to access test interval.
3. The inflation pressure to be applied to the top and bottom packers; the top and bottom packers may need to be inflated to different inflation pressures (see the section "9.7 Inflating Packers to Initiate a Test" on page 89).
4. Date and time the transducer "bleed" valves are pressurized/open (see section "4.2.2 Middle- and Bottom-Zone Transducers" on page 21 for a discussion of the operation of the transducer "bleed" valves, and section "10. Procedures for Hydraulic Testing and Geochemical Sampling in Boreholes" on page 92 for additional information on operating the transducers "bleed" valves during testing).
5. Date and time of the start of inflation of the top and bottom packers.
6. Date and time the packers are inflated to their target pressures (see the section "9.7 Inflating Packers to Initiate a Test" on page 89).
7. Date and time the pressure on the transducer "bleed" valve is reduced/closed (see section "4.2.2 Middle- and Bottom-Zone Transducers" on page 21 for a discussion of the operation of the transducer "bleed" valves, and section "10. Procedures for Hydraulic Testing and Geochemical Sampling in Boreholes" on page 92 for additional information on operating the transducer "bleed" valves during testing).
8. Date and time of the start of the hydraulic perturbation in the test interval (pumping, fluid injection, application of a slug of water).

9. Date and time of any changes in the operation of the test, for example, increasing/decreasing pumping rate, pressure applied to fluid reservoir tank during fluid-injection tests, and changing from one flow meter to the other flow meter using the three-way valve on the flow meter panel.
10. Date and time the hydraulic perturbation is stopped.
11. Date and time of pressurizing/opening the transducer “bleed” valves after the completion of a test (see section “4.2.2 Middle- and Bottom-Zone Transducers” on page 21 for a discussion of the operation of the transducer “bleed” valves, and section “10. Procedures for Hydraulic Testing and Geochemical Sampling in Boreholes” on page 92 for additional information on operating the transducer “bleed” valves during testing).
12. Date and time of starting the deflation of the top and bottom packers.
13. Date and time the top and bottom packers are deflated to their target pressures (see the section “9.8 Deflating Packers to End a Test” on page 91).

9. Deploying the Downhole Components

Lowering the downhole components of the Multifunction BAT^3, including the tubing and cables, requires a series of steps to insure that equipment is not damaged and testing with the Multifunction BAT^3 is conducted properly and safely. These steps include choosing a test interval; preparing the downhole components, cables, and tubing; preparing the fluid reservoir tank, if fluid is to be injected into the test interval; calculating the length of the cable or pipe needed to lower the borehole equipment to the desired depth in the borehole; calculating the operating pressures for the packers and the downhole valves; lowering the downhole components into the borehole; conducting measurements for field calibration of pressure transducers; setting the top zone transducer in the borehole prior to the start of testing; and inflating packers to initiate a test. After the hydraulic testing or geochemical sampling is conducted at a specific interval in the borehole, the packers are deflated, and equipment is moved to the next interval in the borehole for testing. These operations are described in the following sections. A description of the operation of the equipment to conduct hydraulic tests and geochemical sampling is presented in the section “10. Procedures for Hydraulic Testing and Geochemical Sampling in Boreholes” on page 92.

9.1 Choosing a Test Interval

Prior to assembling the downhole components of the Multifunction BAT^3, there should be a knowledge of borehole conditions to guide the selection of the dimension of a test interval. If necessary, the length of the test interval can be adjusted to account for borehole conditions by adding an extension pipe above the bottom borehole packer (see the section “4.8 Test-Interval Length” on page 34).

In general, it is advantageous to select a test interval length that can be applied over the entire length of the borehole for all the testing that is planned. If this is not possible due to changes in borehole conditions with depth in the borehole, the downhole components of the Multifunction BAT^3 will need to be removed from the borehole and the length of the test interval adjusted by changing the length of the extension pipe above the bottom packer. Figure 45 shows an example of test intervals used for fluid-injection testing conducted in a borehole in crystalline rock along with the caliper log and the interpretation of the acoustic televiewer log of the borehole walls. In this instance the test intervals are all the same length. The test intervals are chosen to isolate closely spaced fractures and estimate their hydraulic properties. The test interval also is chosen such that the position of the top and bottom packers of the downhole equipment are not damaged on rough sections of the borehole wall. A discussion of choosing test intervals is given in the section “7.1 Borehole Geophysical Logs” on page 62.

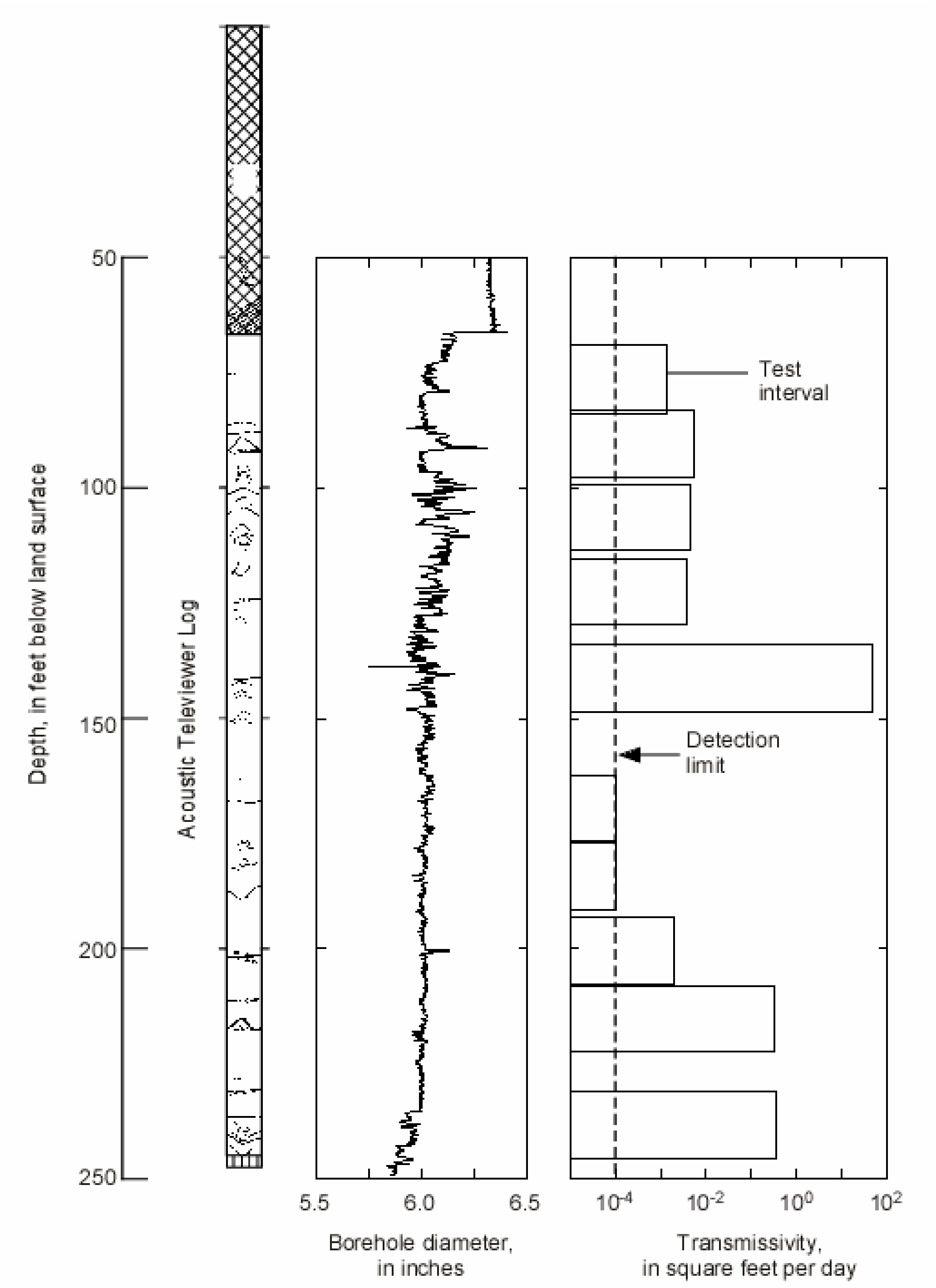

Figure 45. Diagram of borehole geophysical logs (caliper and acoustic televiewer) and the location of test intervals in borehole FSE9 in the vicinity of Mirror Lake, Grafton County, New Hampshire.

Once a test interval is chosen, the length of the cable or pipe needed to lower the equipment to the desired location below an assumed datum needs to be calculated; an assumed datum could be the top of the surface casing or land surface. It is important that the geophysical logs, in particular, the caliper log and the logs of the features on the borehole walls, are referenced to this datum. In addition, the length of the borehole components of the Multifunction BAT^3 will need to be known with precision to calculate the length of the cable or pipe needed to lower the borehole components and locate the packers at the proper depth in the borehole.

9.2 Preparing the Downhole Components, Cables, and Tubing

The section "4.7 Connecting Downhole Components" on page 29 describes the configuration of the downhole components and the union ball fittings used to connect the downhole components of the Multifunction BAT^3. The sections "4.9 Connecting Tubing" on page 35 and "4.10 Summary of Cables and Tubing Extending to Land Surface" on page 40 describe the pressure transducer and pump cables and tubing that are connected to the Multifunction BAT^3. The length of the test interval, and the height of the apparatus used to hoist the downhole equipment and lower it down the borehole, will dictate whether the downhole components can be completely assembled on the ground prior to lowering it down the borehole, or if downhole components need to be hoisted in the air and assembled as they are lowered down the borehole. A further discussion of this topic is given in the section "9.4 Lowering the Downhole Components in a Borehole" on page 84.

The downhole equipment should be prepared for deployment near the borehole by connecting the downhole components to the extent that they can be hoisted by the apparatus that will lower them down the borehole. The uphole end of the pressure transducers should be connected to the data-acquisition panel, and the uphole end of the pump cable should be connected to Grundfos power converter. The tubing used to inflate packers and operate the downhole valves should be properly connected to the downhole components, and the uphole ends of these tubes should be connected to the pressure manifold. A source of compressed gas should also be connected to the pressure manifold. The uphole end of the tubing connected to the pump should be connected to an appropriate flowmeter, if pumping is to be conducted, and the uphole end of the tubing from fluid-injection valve should be connected to the plate with Flowmeters 1 and 2, if fluid-injection tests are to be conducted. Tubing connections between the fluid reservoir tank and the plate with Flowmeters 1 and 2 should also be made; the section "9.3 Preparing the Fluid Reservoir Tank for Fluid Injection" on page 83 provides additional information on preparing the fluid reservoir tank.

If it is necessary to rinse or decontaminate the downhole equipment prior to lowering it in the borehole for the collection of water samples for geochemical analyses or characterizing hydraulic properties of the formation, the procedures for decontaminating the downhole equipment, tubing and cables should be conducted. In addition, decontamination of the cable or pipe needed to lower the equipment in the borehole should be conducted, if necessary. After decontamination, the downhole components, tubing, cable and hoisting apparatus should be placed on tarpaulin or plastic sheeting to maintain their clean status.

Finally, prior to deploying the downhole equipment in the borehole, the tubing and cables that are attached to the downhole components should be configured in the vicinity of the borehole to allow the downhole components to move readily down the borehole. The downhole components weigh several hundred pounds, thus, any unexpected rapid movement of the equipment down the borehole will drag tubing and cables down the borehole as well. The tubing and cables should be positioned in the vicinity of the borehole such that any unexpected rapid movement of the borehole equipment down the borehole will not result in injury to the equipment operators or damage to the equipment at land surface.

9.3 Preparing the Fluid Reservoir Tank for Fluid Injection

If water is to be injected between the packers to estimate hydraulic properties of the test interval, or as part of a tracer test, the tubing from the fluid reservoir tank to the fluid-injection valve in the fluid-injection shroud must be free of air. If fluid injection is not planned during the borehole testing, then this step can be skipped in the preparation of the Multifunction BAT^3 for use in a borehole.

A description of a fluid reservoir tank is given in the section "7.7 Fluid Reservoir Tank" on page 67. Information on filling the fluid reservoir tank with water is also given in that section. Prior to lowering the downhole components of the Multifunction BAT^3 down a borehole, the injection tubing that leads to the fluid-injection valve must be filled with water to insure that no air is injected in the test interval. Filling the injection tubing first requires the assembly of the downhole equipment and connecting the tubing and electrical cables that lead uphole to the data-acquisition equipment and the pressure manifold. The borehole equipment can either be horizontal (on the ground), or it can be extended in the air and hanging in the borehole. Because of the resistance to fluid movement from the fluid-injection tubing, a pressure greater than atmospheric pressure should be applied to the water surface of the fluid reservoir tank to force the water from the reservoir tank through the fluid-injection tubing to remove the air from the tubing. The tubing connections to the fluid reservoir tank for applying a pressure greater than atmospheric pressure are discussed in the section "5.7.3 Tubing Connections to the Fluid Reservoir Tank" on page 59.

To fill the injection tubing with water, the gate valve at the outlet of the fluid reservoir tank is opened and the fluid-injection valve is actuated by applying pressure to the valve through the pressure manifold; water can then run from the fluid reservoir tank through the injection tubing and out the injection valve between the top and bottom packers. Water is run through the injection tubing from the fluid reservoir tank until all of the air is forced out of tubing; the air is forced through the tubing and exits at the injection valve. If the injection tubing is transparent, the tubing can be inspected for air bubbles as the water is flushed through the tubing.

After insuring that all the air is forced from the injection tubing, the applied air pressure is removed from the air-actuated fluid-injection valve, which closes the valve. The injection line is filled with water and the equipment can be lowered downhole for conducting fluid-injection tests or tracer tests.

If fluid-injection testing is being conducted, the water level in the fluid reservoir tank should be inspected on a regular basis. When the water level in the fluid reservoir is low, the reservoir tank should be refilled with water to insure that air is not injected into the tubing leading to the fluid-injection valve. The method of filling the tank that is discussed in the section "7.7 Fluid Reservoir Tank" on page 67 can also be applied if the downhole components of the Multifunction BAT^3 are at depth in a borehole. If pressure above atmospheric pressure is applied to the water surface of the fluid reservoir tank during fluid injection, the air pressure applied to the fluid reservoir needs to be reduced to atmospheric pressure before filling the tank.

If during fluid-injection testing, air is allowed to enter the fluid-injection tubing, the air will need to be forced from the fluid-injection tubing before any additional fluid-injection tests can be conducted. To force air out of the fluid-injection tubing with the Multifunction BAT^3 in the borehole, the fluid reservoir will have to be refilled using the procedure discussed in the section "7.7 Fluid Reservoir Tank" on page 67. With the top and bottom packers deflated, the fluid-injection valve is opened by applying the appropriate pressure to the valve actuator (see the section "4.5 Fluid-Injection Apparatus" on page 27 for a discussion of the pressure needed to open the fluid-injection valve). Because the fluid-injection valve is below land surface, water from the fluid reservoir tank will flow through the fluid-injection tubing without applying pressure (above atmospheric pressure) to the water surface in the fluid reservoir tank. By opening the fluid-injection valve, water from the fluid reservoir tank is forced through the tubing and air in the tubing is forced out through the fluid-injection valve. The air being forced out of the fluid-injection valve will result in air bubbles rising to the water surface in the borehole. The air bubbles rising to the water surface in the borehole will produce a distinctive sound of bubbles popping in the borehole. When this sound stops, the fluid-injection tubing should be completely filled with water, and fluid-injection testing can then continue.

9.4 Lowering the Downhole Components in a Borehole

Depending on the dimension of the test interval and the type of equipment used to lower the downhole components of the Multifunction BAT^3 in the borehole, the downhole components of the Multifunction BAT^3 can be assembled on the ground or by hanging the components in the air and connecting them as they are lowered into the borehole. If the total length of the downhole components of the Multifunction BAT^3 is longer than the height of the hoisting apparatus used to lower the equipment in the borehole, the borehole components and tubing will have to be connected as the components are lowered in the borehole. The components are connected at the locations of the union ball fittings. In connecting components, the nut on the union ball fitting is used to tighten the connection so that the components, themselves, do not have to be rotated. Wrenches are used to tighten the nuts on the union ball fittings. The components at the bottom of the downhole configuration of the Multifunction BAT^3 will have to be lowered in the borehole first and secured at the top of the well casing, and the proper tubing connections will have to be made. Under these circumstances it is best to have the downhole components of the Multifunction BAT^3 configured on the ground along with the necessary tubing in the order that they will be lowered into the borehole. It should be noted, however, that the transducer shrouds, the top packer and the pump shroud will have to be connected using the union ball fittings between these components prior to raising them for deployment in the borehole, because the pump cable is threaded through these components.

If the hoisting apparatus used to lower the downhole components of the Multifunction BAT^3 is tall enough to raise the entire downhole configuration of the Multifunction BAT^3, the downhole components and tubing connections can be assembled on the ground, and then lowered in the borehole (fig. 46). When raising the equipment from its horizontal position on the ground, support should be provided at the union ball fittings, as these connections will be subject to greatest stress in raising the equipment from a horizontal to vertical position (fig. 47).

Figure 46. Photograph (courtesy of John Jaacks) of the downhole components of the Multifunction BAT^3 assembled on the ground adjacent to a borehole prior to lowering the downhole components in the borehole.

Figure 47. Photograph (courtesy of John Jaacks) of the support needed while raising the downhole components of the Multifunction BAT^3 off the ground in preparation of lowering it into a borehole.

The downhole equipment can be lowered in a borehole using either a cable or steel pipe. In general, it is advantageous to use steel pipe to lower the equipment in the event that the equipment becomes lodged in the borehole. When using cable to lower the equipment, pulling on the cable is the only force that can be applied to free the equipment, if it becomes lodged in a borehole. When using steel pipe, however, the equipment can be pushed, pulled or rotated in the event that it becomes lodged in a borehole.

As the equipment is lowered in a borehole and the top and bottom packers are submerged below the water surface in the borehole, compressed gas will need to be added to the top and bottom packers. Without applying pressure to the packers, the fluid pressure of the water column above the packer in the borehole will collapse the flexible bladder of the packer. If the fluid pressure of the water column in the borehole collapses the flexible bladder of the packer, the bladder will drag along the borehole wall, which may damage the packer bladder and make movement of the apparatus in the borehole difficult. Because the top packer will be at a different elevation in the borehole than the bottom packer, the pressure applied to the top and bottom packers will need to be calculated separately.

The pressure applied to the packers as they are lowered in the borehole can be calculated by converting the height of the water column above the packer to an equivalent pressure. The following equation can be used to calculate the pressure that needs to be applied to the packer for a given height of water above it in the borehole:

$$P_{ambient-packer-pressure} = X\ [ft, H_2O] \times \frac{1\,[psi]}{2.31\,[ft, H_2O]} \qquad (3)$$

where $P_{ambient\text{-}packer\text{-}presure}$ is the pressure (in psi) that is applied to the packer to counteract the ambient fluid pressure at a given depth below the water surface in the borehole, X is the depth below the water surface in the borehole in feet, and 1 psi is approximately 2.31 ft of water. For example, if the packer is located at 50 ft below the water surface in the borehole, the packer will need to be inflated to approximately 22 psi to counteract the pressure of the fluid in the borehole at that depth. In general, the pressure applied to the packers, as the equipment is lowered in the borehole, needs to be adjusted with changes in depth of approximately 20 ft. The packers will not completely collapse and drag on the borehole walls if the applied pressure in the packer is approximately 10 psi less than the surrounding fluid pressure. Caution needs to be exercised to avoid over inflating the packers as the equipment is lowered in the borehole. Applying pressure to the packers, approximately 10 psi above the fluid pressure at a particular depth in the borehole, may lead to the packer bladder dragging on the borehole wall, especially along rough sections of the borehole. Overinflating the packers as the equipment is lowered in the borehole may damage the packer bladders and lead to difficulty in moving the equipment in the borehole.

As the components of the Multifunction BAT^3 are lowered in the borehole, the tubing and cables connected to downhole components will need to be fed down the borehole as well. The tubing and cables need to be kept taught to avoid being damaged against the borehole wall when lowering or raising the equipment in the borehole. The tubing and cables should be bundled and secured against the cable or pipe used to lower the downhole components of the Multifunction BAT^3. Plastic cable ties should be used to bundle the tubing and cables, as tape and other adhesive products can leave a residue which may adversely affect some types of geochemical sampling. Even if geochemical sampling is not to be conducted at a particular field site, the downhole equipment including the transducer and pump cables may eventually be used at other field sites where such considerations are warranted.

To facilitate the deployment of the equipment down the borehole, the tubing and cables should be bundled and laid out on a clean surface, such as plastic sheeting, in the vicinity of the borehole such that the tubing and cable bundle can be fed down the borehole easily without interfering with the equipment operator. In addition, because the downhole components weigh several hundred pounds, any unexpected rapid movement of the equipment down the borehole will drag tubing and cables down the borehole as well. The tubing and cables should be positioned in the vicinity of the borehole such that any unexpected rapid movement of the borehole equipment down the borehole will not result in injury to the equipment operators or damage to equipment at land surface.

9.5 Field Calibration of Pressure Transducers

Current laboratory calibrations of the pressure transducers included in the Multifunction BAT^3 are given in table 1 and discussed in the sections “4.2.1 Top-Zone Transducer” on page 19 and “4.2.2 Middle- and Bottom-Zone Transducers” on page 21. Updates to the laboratory transducer calibrations are provided in a calibration library that accompanies the BAT^3 Analyzer (Winston and Shapiro, 2007). The laboratory calibrations were conducted by applying a known pressure to the transducer sensor and recording the millivolt response and the barometric pressure at the time of the calibration. The transducers measure absolute pressure, thus, they measure atmospheric pressure when they are out of water, and the atmospheric pressure needs to be subtracted to calculate the fluid pressure applied to the transducer. The laboratory calibration for each transducer is a linear regression between the applied pressure and the measured millivolt response (for a given excitation voltage).

The laboratory calibrations can be used for the purpose of converting millivolt responses of the transducers to the fluid pressure measured during borehole testing. It is recommended, however, that field calibrations of the transducers also be conducted to insure that the transducers are operating properly. The field calibrations can be calculated using the BAT^3 Analyzer. Field calibrations also can be introduced in the BAT^3 Analyzer to convert the millivolt responses of the pressure transducers to the fluid pressure acting on the transducer sensor (Winston and Shapiro, 2007).

9.5.1 Middle- and Bottom-Zone Transducers

Field calibrations of the middle- and bottom-zone pressure transducers are conducted by taking measurements of the water level as the borehole equipment is lowered in the borehole. Lowering the borehole equipment in the borehole places the middle- and bottom-zone transducers (located in the transducer shrouds) at greater depths below the water surface in the borehole. Measurements of the water level in the borehole below a given datum can then be used in a linear regression with the millivolt responses recorded by the data-acquisition equipment to determine a field calibration for the middle- and bottom-zone transducers.

To conduct a field calibration of the middle- and bottom-zone transducers as the borehole equipment is being lowered in the borehole, the pressure transducer cables should be connected to the data-acquisition panel and the data-acquisition equipment should be recording the responses of the pressure transducers. The section “8. Data Acquisition and Visualization” on page 70 discusses the procedures needed to record the digital records from the pressure transducers. In addition, the tubing attached to the transducer “bleed” valves should be connected to the pressure manifold so that the transducer “bleed” valves can be opened with an applied pressure to remove any air trapped in the tubing extending below the transducer sensor (see the discussion of the operation of the transducer “bleed” valves in the section “4.2.2 Middle- and Bottom-Zone Transducers” on page 21).

With the borehole equipment at a stationary location and with the packers deflated, the water level in the borehole below a given datum should be measured manually and recorded; the electric water level sounder that is shipped with the Multifunction BAT^3 can be used for this purpose. The timing of the manual water-level measurement should coincide with the recording interval associated with the Campbell Scientific CR23X Data Logger specified in the data-acquisition program. For example, if the recording interval of the data logger is 30 seconds, the data logger queries the transducer at 30 second intervals starting on an even minute. Consequently, it is crucial that the clock used to note the time of manual water-level measurements be synchronized with the laptop computer and data logger. At the time of the manual water-level measurement, the depth of the middle- and bottom zone transducers in the borehole should be noted; the depth of the middle-zone transducer can be taken as the bottom of the top transducer shroud, and the depth of the bottom-zone transducer can be taken as the bottom of the lower transducer shroud (fig. 9). In general, transducer calibration measurements should be made prior to inflating the packers at locations where borehole testing is to be conducted. Additional manual measurements of water levels can also be made following the procedures noted above as the equipment is raised or lowered in the borehole. The BAT^3 Analyzer can be used to automatically retrieve millivolt responses from the digital data at specified times and calculate the linear regression between the water level in the borehole and the millivolt response of the transducers (Winston and Shapiro, 2007). The calibration procedure implemented in the BAT^3 Analyzer also can account for barometric pressure in calculating the calibrations for the transducers.

9.5.2 Top-Zone Transducer

A field calibration of the top-zone transducer can also be conducted. The top-zone transducer, however, is not attached to the borehole equipment as it is lowered into the borehole. The top-zone transducer is lowered down the borehole after the downhole components of the Multifunction BAT^3 are placed at the desired depth for borehole testing.

A field calibration of the top-zone transducer can be conducted with or without the downhole components of the Multifunction BAT^3 in the borehole. The cable from the top-zone pressure transducer should be connected to the data-acquisition panel and the data-acquisition equipment should be recording the responses of the pressure transducers. The section “8. Data Acquisition and Visualization” on page 70 discusses the procedures needed to record the digital records from the pressure transducers.

The depth to the water surface in the borehole should be measured using the electric water-level sounder that is shipped with the Multifunction BAT^3. The length of the top-zone transducer cable should then be measured so that the top-zone transducer can be lowered in the borehole so that it is at least 1 ft below the water surface. With the top-zone transducer at a stationary location in the borehole, the water level in the borehole below a given datum should be measured manually and recorded. The timing of the manual water-level measurement should coincide with the recording interval of the data-acquisition program for the Campbell Scientific CR23X Data Logger. For example, if the recording interval of the data logger is 30 seconds, the data logger queries the transducer at 30 second intervals starting on an even minute. Consequently, it is crucial that the clock used to note the time of manual water-level measurements be synchronized with the laptop computer and data logger. Additional manual measurements of water levels should be made by lowering the top-zone transducer in the borehole at 1 ft increments and manually measuring the water level to coincide with the recording interval of the data logger. The BAT^3 Analyzer can be used to automatically retrieve millivolt responses from the digital data at specified times and calculate the linear regression between the water level in the borehole and the millivolt response of the transducers (Winston and Shapiro, 2007). The calibration procedure implemented in the BAT^3 Analyzer also can account for barometric pressure in calculating the calibration for the transducer.

9.6 Setting the Top-Zone Transducer in the Borehole

The top-zone transducer is not connected to the downhole components of the Multifunction BAT^3. Once the downhole components of the Multifunction BAT^3 have been lowered in the borehole to the desired location, and prior to the inflation of the packers, the top-zone transducer should be lowered in the borehole so that it is at least several feet below the water surface in the borehole. The position of the top-zone transducer, however, should be above the shroud that houses the middle-zone transducer to avoid being tangled in the downhole equipment. The user can measure a length of the transducer cable above the transducer sensor and mark it with a cable tie for reference; however, lowering the transducer to this reference mark may not necessarily mean that the transducer sensor is at the desired depth. The transducer cable may be impeded by the pipe, cables and tubing extending down the borehole. The user should check to see that the top transducer is below the water surface prior to the start of testing by monitoring the responses of the transducer. The BAT^3 Analyzer can be used to verify if the top-zone transducer is positioned below the water surface of the borehole. The BAT^3 Analyzer shows digital and graphical displays of the transducer responses in real time.

After lowering the top-zone transducer in the borehole to the desired depth, the transducer cable should be secured at land surface so that the transducer sensor does not move during testing. Plastic cable ties or other non-adhesive means of securing the top-zone transducer cable should be used for this purpose, as adhesive products may yield a residue that adversely affects water chemistry if the transducer cable is in contact with the water in the borehole.

The depth at which the top-zone transducer should be located below the water surface in the borehole will depend on the hydraulic response that arises from the testing conducted in the test interval. The top zone transducer is used to monitor hydraulic responses above the top packer and check if the packers have made a suitable seal against the borehole wall, or if fractures intersecting the test interval are in hydraulic communication with the borehole above the top packer. In general, placing the top-zone transducer at least 5 ft below the water surface should be sufficient to check for hydraulic responses due to fluid injection or pumping in the test interval.

9.7 Inflating Packers to Initiate a Test

The top and bottom packers are inflated separately through tubes that extend from the packers to land surface. The pressure that must be applied to each packer depends on the ambient fluid pressure at the position in the borehole, and the type of test that is to be conducted. Because the top and bottom packers are separated in the Multifunction BAT^3 and the distance between packers can be adjusted to accommodate borehole conditions, the top and bottom packers may need to be inflated to different pressures. Calculations for the appropriate inflation pressure should be made for top and bottom packer separately.

For the Roctest YEP 4.75 packer, the inflation pressure to form a suitable seal against a smooth borehole wall should be approximately 80 psi above the ambient fluid pressure. The section “9.4 Lowering the Downhole Components in a Borehole” on page 84 provides a relation for calculating the ambient fluid pressure acting on a packer at a given depth below the water surface in the borehole. For example, if the (top or bottom) packer is located approximately 50 ft below the water surface in a borehole, the ambient fluid pressure is approximately 22 psi, and the packer should then be inflated to approximately 102 psi.

9.7.1 Fluid-Injection Tests

Inflating the top and bottom packers to approximately 80 psi above the ambient pressure is suitable for conducting hydraulic tests under ambient hydraulic conditions in the borehole, such as measuring the ambient hydraulic head between two packers. If fluid injection is conducted in the test interval by injecting water from the fluid reservoir at land surface, the fluid pressure in the test interval will increase during the test and the difference between the packer pressure and the fluid pressure in the test interval will be less than 80 psi. The increase in fluid pressure due to fluid injection will be approximately equal to the height of the fluid reservoir above the water surface in the borehole, plus the air pressure that is applied to the water surface in the fluid reservoir, if a pressure greater than atmospheric pressure is applied to the water surface of the fluid reservoir tank. For example, if the depth to water in the borehole is approximately 20 ft below land surface, and the fluid reservoir is at land surface with only atmospheric pressure applied to the water surface in the fluid reservoir, then the pressure in the test interval will be approximately 9 psi above the ambient pressure in test interval (due to the elevation of water above the test interval). Thus, instead of 80 psi above the ambient fluid pressure at the test interval, the top and bottom packers should be inflated to approximately 89 psi above the ambient fluid pressure at their positions in the borehole. In this same example, if approximately 15 psi (above atmospheric pressure) is applied to the water surface of the fluid reservoir, then the pressure in the test interval will be approximately 24 psi above the ambient pressure in the test interval, and the packers should be inflated to approximately 104 psi above the ambient fluid pressure at their positions in the borehole. The section “9.4 Lowering the Downhole Components in a Borehole” on page 84 gives a relation for calculating the ambient fluid pressure acting on a packer at a given depth below the water surface in the borehole.

9.7.2 Fluid-Withdrawal Tests

If instead of fluid injection, water is withdrawn from the test interval using the submersible pump for either geochemical sampling or hydraulic testing to identify hydraulic properties of the test interval, the fluid pressure in the test interval during the test is reduced and the difference between the fluid pressure in the test interval and the pressure in the packer will exceed 80 psi. In general, exceeding the 80 psi differential pressure between the inflation pressure of the packer and the ambient fluid pressure at the packer location will not damage the packers.

The maximum depth that the Multifunction BAT^3 can be deployed in a borehole is approximately 300 ft. If the borehole is filled to the top of the casing with water, the maximum drawdown in the test interval that could arise as a result of pumping is approximately 300 ft of water, or approximately 130 psi. Thus, the differential pressure between the inflation pressure of the packer and the pressure in the test interval during pumping would be at most 210 psi. In most situations of pumping from a test interval, the differential pressure will be considerably less. In general, this differential pressure will not damage the packers, and for simplicity, it is recommended the packers be inflated to approximately 80 psi above the ambient fluid pressure at the packer location, using the height of water above the packer as a measure of the ambient fluid pressure. The section "9.4 Lowering the Downhole Components in a Borehole" on page 84 gives a relation for calculating the ambient fluid pressure acting on a packer at a given depth below the water surface in the borehole. It should be remembered that the top and bottom packers are located at different depths below the water surface in the borehole, and the ambient fluid pressure acting on each packer will be different.

9.8 Deflating Packers to End a Test

After conducting a test in a borehole where packers have been inflated, it is necessary to deflate the packers prior to moving the downhole equipment in the borehole and conducting another test. Deflating the packers is conducted by "venting" the valves on the pressure manifold that are connected to the top and bottom packers. Turning the valves to the vent position opens the valves to the atmosphere and pressure in the packer is reduced. The pressure in the packers, however, cannot be reduced to atmospheric pressure. The Roctest YEP 4.75 packers have no backing behind the flexible bladder, thus the ambient fluid pressure pushing on the packer bladder will tend to compress and flatten the bladder, if the pressure in the packer is less than the ambient fluid pressure at the depth of the packer in the borehole. If the packer bladder is flattened, it may become slightly wider than 6 inches in the dimension that is flattened, and it will drag on the borehole wall. Dragging the packer bladder on the borehole wall will damage the bladder and may cause the borehole equipment to become lodged in the borehole.

After completing a test in the borehole, the inflation pressure of the top and bottom packers should be reduced to the ambient fluid pressure at their depths in the borehole (see the section "9.4 Lowering the Downhole Components in a Borehole" on page 84 for information on calculating the ambient fluid pressure acting on a packer at a given depth below the water surface in the borehole). Because the top and bottom packers are separated in the Multifunction BAT^3 and the distance between packers can be adjusted to accommodate borehole conditions, the top and bottom packers may need to be deflated to different pressures. Calculations for the appropriate pressure should be made for the top and bottom packer separately.

9.9 Moving the Equipment to a New Test Interval

After completing the testing in a given test interval and deflating the packers to the appropriate pressure for their depth in the borehole, the downhole components of the Multifunction BAT^3 can be moved to a new location in the borehole to conduct another test. Prior to moving the borehole equipment, the top-zone transducer should be removed from the borehole, so that it does not become tangled when raising or lowering the downhole equipment in the borehole.

Prior to moving the borehole equipment to the new test interval, the length of pipe or cable needed to be added or removed from the borehole should be calculated so that the equipment can test fractures at the next interval in the borehole. If the current length of the test interval is not compatible with the borehole conditions at the next testing location in the borehole, the borehole equipment should be removed from the borehole and the length of the test interval should be adjusted by changing the length of the extension pipe (see the discussion in the section "7.8 Extension Pipe" on page 69).

When moving the equipment up or down the borehole over distances greater than 20 ft, the pressure in the packers will need to be adjusted so that the pressure applied to the packers is approximately equal to the ambient fluid pressure at the depth of the packer in the borehole. If the equipment is being raised in the borehole, this will require reducing the pressure in the packers. If the equipment is being lowered in the borehole, then additional pressure should be applied to the packers. Because the top and bottom packers are separated by the length of the test interval, the pressure applied to the top and bottom packers when moving the equipment in the borehole will need to be calculated separately (see the discussion in the section "9.4 Lowering the Downhole Components in a Borehole" on page 84).

In general, when either raising or lowering the downhole equipment after the end of one test, it is good practice to first lower the equipment a few feet to insure that the packers are sufficiently deflated to insure that the downhole equipment can move easily in the borehole. If the packers have been deflated to the proper ambient pressure, the weight of the downhole components should be sufficient to have the equipment move down the borehole. If the packers have not been deflated to the proper ambient pressure after testing, then the packer bladders may rub against the borehole walls, resulting in the downhole equipment not moving once the brake holding the pipe or cable has been released. Under conditions of rough borehole walls, packer bladders may not move easily down the borehole and some added force or torque may be needed to lower the equipment in the borehole.

When moving the downhole components of the Multifunction BAT^3 up or down the borehole, the tubing and cables that extend down the borehole should be kept taught and bundled against the cable or pipe used to the raise or lower the downhole testing apparatus. The tubing or cables may become tangled in the downhole equipment if they are not tightly attached to the hoisting cable or pipe. In addition, because the downhole components weigh several hundred pounds, any unexpected rapid movement of the equipment down the borehole will drag tubing and cables down the borehole as well. The tubing and cables should be positioned in the vicinity of the borehole such that any unexpected rapid movement of the borehole equipment down the borehole will not result in injury to the equipment operators or damage to the equipment at land surface.

10. Procedures for Hydraulic Testing and Geochemical Sampling in Boreholes

The Multifunction BAT^3 can be used to measure ambient hydraulic head, or conduct hydraulic tests that either inject or withdraw water from the borehole for the purpose of estimating hydraulic properties of the fractures in the test interval. The Multifunction BAT^3 also can be used to withdraw water from a borehole for the purpose of collecting water samples for geochemical analyses. In the following sections, the procedures of applying the Multifunction BAT^3 for various types of testing are discussed.

10.1 Ambient Hydraulic Head

The hydraulic head in an open borehole is a weighted average of the hydraulic heads associated with all fractures intersecting the open borehole, with the most weight being given to those fractures with the highest transmissivity (Shapiro, 2002b). Understanding the variability in the hydraulic head over the depth of a borehole can aid in understanding the ground-water flow regime and designing the installation of equipment for long-term water-level monitoring.

Usually the estimation of the hydraulic head as a function of depth in a borehole is conducted in concert with other types of hydraulic tests, or the collection of water samples for geochemical analyses. The configuration of the downhole equipment and the tubing connections will depend on the type of hydraulic tests that will be conducted. The sections “4.7 Connecting Downhole Components” on page 29, “4.9 Connecting Tubing” on page 35, and “4.10 Summary of Cables and Tubing Extending to Land Surface” on page 40 summarize the configuration of the downhole components of the Multifunction BAT^3 and the tubing connections for various types of hydraulic tests.

10.1.1 Procedure

To determine the hydraulic head in a discrete interval of the borehole, the downhole equipment should be lowered to the desired location in the borehole, making use of the geophysical logs to choose the test interval and the length of the test interval (see the section “7.1 Borehole Geophysical Logs” on page 62). The geophysical logs should be checked to see that the packers will not be placed on rough sections of the borehole walls. After positioning the downhole equipment at the desired location in the borehole, the following steps should be taken and the documentation of these steps, including the time at which these steps are conducted, should be kept in a written record (see the section “8.7 Documentation Collected During Borehole Testing” on page 78):

1. Check that the top-, middle-, and bottom-zone pressure transducers, and a 12 V DC battery to power the data logger are connected to the data-acquisition panel.
2. Lower the top-zone transducer below the water level in the borehole (see the section “9.6 Setting the Top-Zone Transducer in the Borehole” on page 89).
3. Open the transducer “bleed” valves by applying an appropriate air pressure to the “bleed” valves through the pressure manifold (see the section “4.2.2 Middle- and Bottom-Zone Transducers” on page 21).
4. If the downhole equipment includes the fluid-injection apparatus, check to see that the fluid-injection valve is closed, that is, no pressure being applied to the fluid-injection valve through the pressure manifold.
5. Manually measure and record the water level in the borehole using the electric water-level sounder shipped with the Multifunction BAT^3; the manual measurement of the water level should coincide with the time that the data logger interrogates and records the downhole pressure transducers.
6. Calculate the target pressures to be applied to the top and bottom packers (see the section “9.7 Inflating Packers to Initiate a Test” on page 89).
7. Inflate the bottom packer to the target pressure.
8. Inflate the top packer to the target pressure.
9. Wait for the fluid pressure in the test interval to stabilize; fluid displacement during the inflation of the packers may result in an increased fluid pressure between the two packers.

10. Close the transducer "bleed" valves by reducing the pressure applied to the transducer "bleed" valves through the pressure manifold; this step hydraulically isolates the test interval between the packers from the remainder of the borehole.
11. Wait for the stabilization in the fluid pressure measured in the test interval. The fluid pressure measured in the test interval is the ambient fluid pressure in the fractures intersecting the borehole.

Once the fluid pressure in the test interval has stabilized, other hydraulic testing can be conducted (see the sections "10.2 Geochemical Sampling" on page 96, "10.3 Single-Hole Hydraulic Test by Fluid Withdrawal" on page 99, "10.4 Single-Hole Hydraulic Test by Fluid Injection" on page 102, "10.5 Pressurized-Slug Test" on page 106, and "10.6 Single-Hole Tracer Test by Fluid Injection Followed by Pumping" on page 109). If other hydraulic tests are not to be conducted after the measurement of the ambient hydraulic head, then the following steps are conducted prior to moving the downhole equipment to the next test interval in the borehole:

12. Open the transducer "bleed" valves by applying pressure to the valves through the pressure manifold.
13. Deflate the top and bottom packers to the target pressure for their depth in the borehole.
14. Remove the top-zone transducer from the borehole.

When pressure is applied to the packers during inflation, water in the borehole will be displaced by the increased size of the packer. Inflating the bottom packer first allows water to be displaced up the borehole, which may result in higher pressures above the bottom packer, if the fractures intersecting the borehole above the bottom packer are not sufficiently permeable to dissipate the pressure perturbation. Increased pressure may also be noticed below the bottom packer, if the fractures below the bottom packer are not sufficiently permeable to dissipate the pressure perturbation. Because there is no free-water surface below the bottom packer, the rise in fluid pressure could be large below the bottom packer, if the fractures below the bottom packer are not sufficiently permeable to dissipate the pressure perturbation caused by the water displacement. The BAT^3 Analyzer can be used to observe the changes in fluid pressure from the downhole transducers during this procedure.

Inflating the top packer will also displace water up the borehole and increase the fluid pressure in the test interval between the two packers. Inflating the top packer after the bottom packer has been inflated, however, reduces the pressure in the test interval due to the displacement of water in comparison to inflating both packers simultaneously.

After both packers are inflated, the open transducer "bleed" valves allows hydraulic communication between the test interval and the intervals above the top packer and below the bottom packer. The increase in fluid pressure in the test interval due to the displacement of water can be dissipated through the open transducer "bleed" valves, however, this pressure dissipation occurs through 0.25-inch-diameter tubing, and thus, the dissipation may not occur rapidly. If there is a large increase in the fluid pressure in the test interval after the inflation of both packers, leaving the transducer "bleed" valves open for a period of time would help dissipate this increase in pressure and would minimize the amount of time that may be needed to reach an ambient pressure in the test interval after the transducer "bleed" valves are closed. A large increase in the fluid pressure in the test interval during the inflation of the top packer is an indication that fractures with low transmissivity intersect the test interval.

Closing the transducer “bleed” valves hydraulically isolates the test interval from the intervals above the top packer and below the bottom packer, provided the packers form a good seal against the borehole walls and fractures intersecting the test interval do not directly connect with other fractures that intersect the borehole above or below the test interval. After the transducer “bleed” valves are closed, the pressure in the test interval will need to recover from the hydraulic perturbation caused by inflating the packers and isolating the test interval from the rest of the borehole. If fractures intersecting the test interval are highly transmissive, the time required for the pressure in the test interval to stabilize could be a few minutes. In contrast, if the fractures are not very transmissive, it could take hours or days. If the fluid pressure in the test interval does not stabilize in a reasonable period of time, other hydraulic tests can still be conducted; however, the inability to achieve the ambient fluid pressure in the test interval should be noted as the trend in the fluid pressure response in the test interval may affect the estimation of the hydraulic properties of the test interval from various hydraulic tests. The BAT^3 Analyzer can be used to observe the changes in fluid pressure in the test interval during this procedure. Changes in fluid pressure in the intervals above the top packer and below the bottom packer may also occur if these sections of the borehole have not been isolated from the test interval.

The ambient hydraulic head in the test interval will be a weighted average of the hydraulic heads of the fractures intersecting the borehole in the test interval; the ambient hydraulic head will be biased to the hydraulic head of the fractures with the highest transmissivity. Ambient hydraulic heads above the top packer and below the bottom packer can also be calculated. If the packers form a good seal against the borehole walls, the ambient hydraulic head measured above and below the test interval would show the hydraulic heads in these intervals without the contribution of the test interval.

10.1.2 Calculating Ambient Hydraulic Head in the Test Interval

The calibrations relating millivolt responses to fluid pressure for the downhole pressure transducers are needed to calculate the ambient hydraulic head in the test interval. A library of laboratory calibrations has been prepared for the transducers that are shipped with the Multifunction BAT^3; this library is included with the BAT^3 Analyzer. Calibrations determined from field measurements can also be conducted. Using these calibrations, the millivolt responses of the transducers can be converted to physically meaningful values, such as the height of water above the transducer sensor. The BAT^3 Analyzer applies these conversions to the measured transducer responses. To calculate the ambient hydraulic head in the test interval, the following steps are performed:

1. Note the time of the manual measurement of the water level in the borehole (below the datum) prior to inflating the packers, and the depth to water in the borehole at that time.
2. Note the digital response of the pressure transducer in the test interval from the data logger at the same time the manual measurement was made.
3. Convert the measured transducer response (at the time the manual measurement was made) to physically meaningful units, for example, as the height of water above the transducer sensor in units of feet or meters. The manual measurement of the water level in the borehole should be converted to the same units of length as the pressure transducer response.

4. Note the transducer response after the fluid pressure in the test interval has stabilized (after the packers have been inflated and after the transducer "bleed" valves have been closed); the transducer response should be converted to physically meaningful units, similar to that discussed above.
5. The transducer response recorded in step 3 is subtracted from the transducer response recorded in step 4. The result is the difference in the hydraulic head between the hydraulically isolated test interval and the open hole hydraulic head.
6. Add the result from step 5 to the water level recorded in the open hole prior to inflating the packers. The result is the hydraulic head in the hydraulically isolated test interval, given as the depth to water below the datum used for the manual measurement.
7. If the elevation of the datum is known, the result from step 6 can be subtracted from the known elevation of the datum to yield the hydraulic head of the test interval, given as an elevation, such as the elevation in feet or meters above mean sea level.

10.1.3 Calculating Ambient Hydraulic Head Above and Below the Test Interval

Steps 1 through 7 used to calculate the ambient hydraulic head in the test interval can also be used to calculate the ambient hydraulic head in the intervals above the top packer and below the bottom packer after the inflation of the packers. To perform this calculation, however, the transducer responses for the top interval or bottom interval would be used in place of the transducer responses for the test interval in the steps given above.

10.2 Geochemical Sampling

Collecting water samples for geochemical analysis by pumping in an open borehole will result in water being drawn preferentially from those fractures with the highest transmissivity, regardless of their location relative to the pump intake (Shapiro, 2002b). The Multifunction BAT^3 allows discrete intervals of a borehole to be isolated hydraulically for geochemical sampling by using packers that seal against the borehole wall. The test interval may still have several fractures between the packers, and water will be drawn preferentially from those fractures in the test interval with the highest transmissivity.

The configuration of the downhole equipment and the tubing connections for geochemical sampling are discussed in the sections "4.7 Connecting Downhole Components" on page 29, "4.9 Connecting Tubing" on page 35, and "4.10 Summary of Cables and Tubing Extending to Land Surface" on page 40. If other types of hydraulic testing are to be coupled with geochemical sampling, the downhole components and tubing of the Multifunction BAT^3 should be configured accordingly.

10.2.1 Procedure

The procedure for measuring the ambient hydraulic head given in the section "10.1 Ambient Hydraulic Head" on page 92 are the first steps that are performed in preparing a selected interval of the borehole for geochemical sampling. The ambient hydraulic head of the test interval should be measured prior to initiating the collection of water samples for geochemical analyses, because such information will provide insight into the hydrogeologic controls on ground-water flow, which are of importance in the interpretation of the geochemical analyses. In addition, the collection of water samples for geochemical analyses by pumping water from the test interval should be conducted such that estimates of the transmissivity of the test interval can be made from the fluid pressure responses. Thus, digital records of the pumping rate from the flowmeter and the fluid pressure responses from the pressure transducers should be recorded.

After conducting the steps to isolate the test interval in the borehole and measure the ambient hydraulic head, the following steps should be taken and the documentation of these steps, including the time at which these steps are conducted, should be kept in a written record (see the section "8.7 Documentation Collected During Borehole Testing" on page 78):

1. Connect the pump cable from the downhole pump apparatus to the Grundfos power converter and connect the power converter to a 120 V AC power source.
2. Check that the tubing leading from the pump is attached to a suitable flowmeter (Flowmeter A or Flowmeter 1) and check that the cable from that flowmeter is connected to the appropriate receptacle on the data-acquisition panel. Also check that a 12 V DC battery is connected to the appropriate receptacle on the data-acquisition panel to power the flowmeter.
3. Turn on the pump using the (red) on/off switch on the Grundfos power converter.
4. Adjust the pumping rate using the variable speed control dial on the Grundfos power converter.
5. Monitor the pumping rate, and the fluid pressures in the test interval, and above and below the test interval to decide on the operation and duration of the test (see the discussion in the section "10.2.2 Purging the Test Interval" on page 97). The calibration and conversion values for the transducers and flowmeters that are supplied with the BAT^3 Analyzer can be used to convert responses from these sensors to physically meaningful values.
6. After collecting water samples for geochemical analyses, terminate pumping by turning off the pump using the (red) on/off switch on the Grundfos power converter.
7. Monitor the fluid pressures in the test interval, and above and below the test interval after the termination of pumping until fluid pressure responses have equilibrated.

After the completion of the steps listed above, the following step should be conducted prior to moving the borehole equipment to the next test interval in the borehole:

8. Open the transducer "bleed" valves by applying pressure to the valves through the pressure manifold.
9. Deflate the top and bottom packers to the target pressure for their depth in the borehole.
10. Remove the top-zone transducer from the borehole.

10.2.2 Purging the Test Interval

At the onset of pumping, water will be removed from the borehole between the two packers, and ground water from the fractures intersecting the test interval will be induced to flow into the borehole, because of the lower hydraulic head in the borehole due to pumping. The water in the borehole between the two packers prior to the start of pumping, however, is not necessarily indicative of the water in those fractures intersecting the test interval. Consequently, a sufficient volume of water must be purged at the onset of pumping prior to collecting a water sample for geochemical analyses that are representative of the water in the formation. Robbins and Martin-Hayden (1991), Reilly and Gibs (1993), Shapiro (2002b) and Wilde (2005) provide suggestions and discuss factors affecting the purging time prior to collecting a water sample that is indicative of the ground water in the formation. In general, the purging time will depend on the pumping rate and the volume of fluid in the test interval; however, geochemical field parameters such as pH, temperature, and specific conductance should be monitored during pumping to establish that the characteristics of the fluid are not changing.

In a 6-inch-diameter borehole, the volume of water in the borehole is approximately 1.5 gallons per linear foot of the borehole; with the borehole testing equipment in the test interval, the volume of water in the borehole will be slightly less than 1.5 gallons per linear foot of the borehole. In general, it is advantageous to minimize the length of the test interval in the Multifunction BAT^3 to reduce the time needed to purge the test interval prior to collecting a water sample for geochemical analyses. The length of the test interval, however, will depend on borehole conditions (see the sections "4.8 Test-Interval Length" on page 34, "7.1 Borehole Geophysical Logs" on page 62, and "9.1 Choosing a Test Interval" on page 80). In addition, the volume of the water in the tubing from the pump to land surface also must be accounted for in calculating the time needed to purge the test interval prior to collecting a water sample. In general, 0.5-inch-diameter tubing will have an inside diameter equal to 0.375 inches, and a volume of approximately 0.00574 gallons per linear foot of tubing. An estimate of the total volume of water resident between the two packers and in the tubing can be calculated from the following equation,

$$V_{resident-fluid} = L\ [ft] \times \frac{1.5\ [gallons]}{[ft]} + M\ \ [ft] \times \frac{0.00574\ [gallons]}{[ft]} \qquad (4)$$

where $V_{resident\text{-}fluid}$ is an estimate of the volume of fluid (in gallons) in the test interval and in the tubing leading from the pump to land surface, L is the length of the test interval in a 6-inch-diameter borehole and M is the length of 0.5-inch-diameter tubing from the pump to land surface.

In some instances, fractures in the test interval may not be sufficiently transmissive to purge the volume of water in the test interval and the tubing, and then collect water samples for geochemical analyses. In general, the pump apparatus included in the Multifunction BAT^3 can provide pumping rates as low as 0.05 gal/min. At this low pumping rate, however, the operation of the pump could result in the temperature of the water being elevated because sufficient water does not flow over the pump in the pump shroud to cool the pump motor. When pumping at low flow rates, the temperature of the pumped water should be monitored and the effect of elevated water temperatures on the geochemical analyses that are to be conducted should be determined. In addition, operating the pump at low-flow rates over an extended period of time may result in the malfunctioning of the pump, because of excessive heating of the pump motor.

Also, when pumping at low pumping rates, the water discharged from the pump will reside longer in the discharge tubing. If the portion of the discharge tubing at land surface is exposed to atmospheric conditions that can raise the temperature of the water in the tubing, the user may also notice a water temperature that is higher than the anticipated ambient ground-water temperature. The user should always attempt to minimize the influence of atmospheric conditions on the pumped water by either minimizing the length of the discharge tube at land surface or insulating the discharge tubing from atmospheric conditions.

If the test interval is not capable of contributing sufficient water to operate the pump, or if the speed of the pump is set too high, a large reduction in the fluid pressure from the ambient fluid pressure at the start of pumping will be noticed in the test interval. The pumping rate should be adjusted so that a positive fluid pressure is maintained in the test interval. Negative pressures induced by large pumping rates or pumping in low-transmissivity intervals could damage the pressure transducer in the test interval and cause dissolved gases in the water in the test interval to come out of solution. If reducing the pumping rate cannot maintain a positive fluid pressure in the test interval, the purging of the test interval should be terminated by turning off the pump, opening the transducer "bleed" valves and deflating the packers.

The time needed to purge the test interval prior to collecting a water sample also may play a role in deciding whether to collect a water sample from a specific test interval in a borehole. For example, at a pumping rate of 0.05 gal/min and with a 6 ft test interval and 300 ft of tubing leading to land surface, it would take approximately 215 minutes to pump a volume of water equal to the volume of the test interval and the tubing. For a 12 ft test interval and 300 ft of tubing extending to land surface and a pumping rate of 0.05 gal/min, the time to pump a volume of water equal to the volume of the test interval and tubing is approximately 395 minutes. Usually, purging the water from the test interval and collecting water samples for geochemical analyses will require pumping a volume of water equal to several times the volume of water in the test interval and tubing, $V_{resident\text{-}fluid}$.

During pumping, the fluid pressure responses above and below the test interval should be monitored. Changes in fluid pressure in the top- and bottom-zone pressure transducers could indicate that the packers are not sealing properly at the borehole wall, or that fractures in the test interval are connected to fractures in the formation that intersect the borehole above or below the test interval. Changes in fluid pressure above or below the test interval that occur immediately at the onset of pumping could indicate packers that are not sealing properly along the borehole wall, or the presence of highly transmissive fractures in the test interval that intersect other highly transmissive fractures that intersect the borehole above or below the test interval. Under this situation, the water that is being pumped is not necessarily indicative of the water in those fractures intersecting the test interval, which could lead to ambiguous interpretations of the geochemistry of the ground water. The length of the test interval may need to be changed either to achieve a good seal with the packers against the borehole walls, or to isolate the interconnected highly transmissive fractures intersecting the borehole.

Fluid pressure changes above or below the test interval that do not occur immediately at the onset of pumping may be the result of fluid pressure responses through the network of fractures in the formation that eventually intersect with fractures in the borehole above or below the test interval. If these fluid pressure responses do not yield large changes in hydraulic head relative to the change in hydraulic head in the test interval, the water collected during pumping could be regarded as being representative of the fractures in the formation immediately adjacent to the test interval.

10.3 Single-Hole Hydraulic Test by Fluid Withdrawal

The transmissivity of highly transmissive fractures intersecting a test interval is estimated by withdrawing water from the test interval and monitoring the pumping rate and the fluid pressures response in the test interval. The configuration of the downhole equipment and the tubing connections for conducting fluid-withdrawal tests are given in the sections "4.7 Connecting Downhole Components" on page 29, "4.9 Connecting Tubing" on page 35, and "4.10 Summary of Cables and Tubing Extending to Land Surface" on page 40. If other types of hydraulic testing are to be coupled with fluid-withdrawal tests, the downhole components and tubing connections for the Multifunction BAT^3 should be configured accordingly.

The procedures for conducting fluid-withdrawal tests using the Multifunction BAT^3 are similar to the procedures discussed in the previous section for collecting water samples for geochemical analyses. The only exception may be that an in-line check valve may be installed in the tubing leading from the pump to land surface. A discussion of the position, purpose, and operation of the in-line check valve is given in the section "4.9.4 Pump Discharge - Water Line" on page 37.

When conducting a hydraulic test by pumping water from the test interval, the in-line check prohibits water in the pump discharge tubing (above the check valve) from re-entering the test interval after the cessation of pumping. This makes it easier to interpret the fluid pressure responses in the test interval after the end of pumping. If fluid re-enters the test interval after the cessation of pumping, an additional hydraulic perturbation is imposed on the fluid pressure response in the test interval.

Also, prior to the start of pumping, the in-line check valve retains water in the tubing up to land surface. Consequently, at the start of pumping, water will immediately be moving through the flowmeter at land surface, and flowmeter readings will be available from the time the pump is first operating. Without the in-line check valve in the pump discharge tubing, water will need to move up the tubing and enter the flowmeter at land surface before accurate flowmeter readings can be measured. When pumping at low flow rates, if the pump discharge tubing is not filled with water initially, the initial pumping rates at the start of the test will not be measured accurately.

If an in-line check valve is installed in the tubing leading from the pump to land surface, then the following steps should be added to the procedure for preparing to measure the ambient hydraulic head given in the section "10.1 Ambient Hydraulic Head" on page 92,

1. When the downhole components of the Multifunction BAT^3 are lowered below the water surface in the borehole, and with the packers deflated, the pump should be turned on (see the section "10.2 Geochemical Sampling" on page 96 for instructions on operating the Grundfos MP1 pump).
2. The pump should be left running until water fills the pump discharge tubing up to land surface and through the flowmeter that will be used to monitor the pumping rate.

These steps should be conducted prior to measuring the ambient hydraulic head in the test interval.

As discussed in the previous section "10.2 Geochemical Sampling" on page 96, during the operation of the pump, the fluid pressure should be monitored in the test interval to insure that the fluid pressure remains positive during pumping. Large changes from the ambient fluid pressure in the test interval and fluid pressures less than zero can arise in test intervals having low transmissivity. The pumping rate should be adjusted using the variable speed control dial on the Grundfos power converter. If a low pumping rate is needed to conduct the hydraulic test to estimate hydraulic properties of the test interval, for example, pumping rates less than 0.1 gal/min, it may be easier to perform a fluid-injection or pressurized-slug test using the Multifunction BAT^3 to estimate the transmissivity of the test interval (see the sections "10.4 Single-Hole Hydraulic Test by Fluid Injection" on page 102 and "10.5 Pressurized-Slug Test" on page 106).

If the pumping rate does not induce a measurable change in the fluid pressure in the test interval, the pumping rate should be increased by using the variable speed control on the Grundfos power converter. The Grundfos Redi-Flo2 pump system is capable of pumping at approximately 9 gal/min against a hydraulic head of approximately 25 feet through 0.5-inch-diameter tubing. Lower pumping rates are achieved for pumping against greater heads. The maximum pumping rate will depend on the height of the water above the pump. Pumping rates of 2.5 gal/min have been achieved with the Grundfos Redi-Flo2 pump system in the Multifunction BAT^3 at depths of 300 ft. In highly transmissive formations, the capacity of the pump configuration on the Multifunction BAT^3 may not be capable of inducing a significant change in the fluid pressure in the test interval to estimate the transmissivity. Pumps with larger capacity than that used in the Multifunction BAT^3 may be needed to estimate the transmissivity in highly transmissive fractures isolated in the test interval.

In the estimation of the hydraulic properties of the test interval from fluid-withdrawal tests, it is advantageous to have a constant pumping rate. If adjustments are made to the pumping rate at the start of the hydraulic test, the test will need to be conducted for a sufficient period of time such that the initial perturbations in the pumping rate do not influence the hydraulic responses in the latter part of the test. Under such conditions, the pumping rate at the end of the test can be regarded as the pumping rate used to estimate the transmissivity of the test interval.

As discussed in the previous section "10.2 Geochemical Sampling" on page 96, during the operation of the pump, the fluid pressure should be monitored above and below the test interval using the top- and bottom-zone transducers. Changes in fluid pressure in the top- and bottom-zone pressure transducers could indicate that the packers are not sealing properly at the borehole wall, or fractures in the test interval are connected to fractures in the formation that intersect the borehole above or below the test interval.

Changes in fluid pressure above or below the test interval that occur immediately at the onset of pumping could indicate packers that are not sealing properly along the borehole wall, or the presence of highly transmissive fractures in the test interval that intersect other highly transmissive fractures that intersect the borehole above or below the test interval. Under such conditions, it may not be possible to estimate the hydraulic properties of fractures intersecting the test interval, because the test interval has not been isolated in the borehole. It may be necessary to adjust the length of the test interval by either increasing or decreasing the length of the test interval to isolate a section of the borehole hydraulically.

Fluid pressure changes above or below the test interval that do not occur immediately at the onset of pumping may be the result of fluid pressure responses through the network of fractures in the formation that eventually intersect with fractures in the borehole above or below the test interval. The magnitude and timing of the pressure responses measured above or below the test interval will play a role in the interpretation of the hydraulic properties of the test interval and the conceptual model of fluid movement in the formation. Winston and Shapiro (2007) discuss several hydrogeologic conceptual models for interpreting the fluid pressure responses in the test interval from pumping.

10.4 Single-Hole Hydraulic Test by Fluid Injection

Fluid-injection tests are used to estimate the transmissivity of the test interval and are conducted by injecting water from a fluid reservoir tank at land surface and monitoring the flow rate and fluid pressure response in the test interval. Fluid-injection tests are usually conducted in test intervals having low transmissivity that cannot be tested by pumping water because the rate of withdrawal would be below the capacity of most pumps. The configuration of the downhole equipment and the tubing connections for conducting fluid-injection tests are given in the sections "4.7 Connecting Downhole Components" on page 29, "4.9 Connecting Tubing" on page 35, and "4.10 Summary of Cables and Tubing Extending to Land Surface" on page 40. If other types of hydraulic testing are to be coupled with fluid-injection tests, the downhole components and tubing of the Multifunction BAT^3 should be configured accordingly.

Prior to conducting a fluid-injection test in a test interval, an ambient hydraulic head measurement should be made using the procedures given in the section "10.1 Ambient Hydraulic Head" on page 92. If fluid-withdrawal tests are to be conducted and an in-line check valve is located in the pump discharge tubing, the steps given in the section "10.3 Single-Hole Hydraulic Test by Fluid Withdrawal" on page 99 should also be included in preparing the downhole components of the Multifunction BAT^3 once they are lowered in the borehole.

The fluid-injection test is conducted by pressurizing the test interval between the packers by injecting water, and then monitoring the fluid pressure response to this hydraulic perturbation. For this reason, all mechanical outlets for the water from the fluid reservoir tank, other than the fluid-injection valve in the fluid-injection apparatus must be sealed. For example, it is extremely important that the fittings used to connect the fluid-injection tubing from the fluid reservoir tank down to the fluid-injection valve be pressure tight so that water does not leak from these fittings. The leaking of water from any of these fittings will result in erroneous estimates of the transmissivity of the test interval. It is also necessary to insure that the fluid injected into the test interval does not exit the discharge tubing from the pump. Therefore, in conducting a fluid-injection test, it is also necessary to cap the end of the pump discharge tubing at land surface with a pressure tight fitting, and insure that all fittings in the pump discharge tubing are pressure tight.

It is also recommended that the fluid-injection equipment be tested for leaks by conducting a test in the surface casing of the borehole. If a sufficient length of the surface casing is not filled with fluid to conduct a fluid-injection test between the packers, then a presumed impermeable section of the borehole can be used for this purpose. A log of the borehole walls to identify fractures would be needed to insure that there are no fractures in the test interval; however, borehole scanning logs may not detect all fractures. The results of conducting a fluid-injection test in the surface casing or an impermeable section of the borehole should show an initial pressurization of the test interval and flow into the test interval, because of the compressibility of the downhole fluid-injection apparatus; however, this would be followed by the flow rate quickly reducing to zero when measured on Flowmeter 2. If a fluid-injection rate is measured when conducting a fluid-injection test in the surface casing, then a leak exists in the downhole equipment, and the equipment should be checked to insure that the fluid-injection valve is operating properly and all possible mechanical outlets for the injected water are properly sealed. The procedures used to conduct a fluid-injection test, which may also be a test conducted in the surface casing or an impermeable section of the borehole, are discussed in the following paragraphs.

After following the procedure to measure the ambient hydraulic head in the test interval, the following steps are performed to conduct a fluid-injection test, which includes recording the time at which these steps are conducted (see the section “8.7 Documentation Collected During Borehole Testing” on page 78):

1. Check that the tubing from the fluid reservoir tank is connected to the valve on the plate with Flowmeters 1 and 2, and check that the fluid-injection tubing leading from the fluid reservoir tank to the downhole fluid-injection valve has been purged of air (see the section “9.3 Preparing the Fluid Reservoir Tank for Fluid Injection” on page 83). Also, check that the manual valve at the outlet of the fluid reservoir tank is open.
2. Check that a pressure-tight cap has been placed at the end of the tubing (at land surface) leading from the downhole pump.
3. Check that the cables from Flowmeters 1 and 2 are connected to the data-acquisition panel, and check that the 12 V DC batteries used to power the flowmeters are also connected to the data-acquisition panel. If the cable from Flowmeter A is connected to the data-acquisition panel for fluid-withdrawal tests or geochemical sampling, disconnect this cable from the data-acquisition panel prior to connecting Flowmeters 1 and 2 to the data-acquisition panel.
4. Check that the proper calibrations and conversion values are used in the BAT^3 Analyzer to visualize the responses for Flowmeters 1 and 2.
5. Check that no pressure is applied to the fluid-injection valve at the start of the test, and that Flowmeters 1 and 2 measure a zero flow rate.
6. Move the three-way valve on the plate holding Flowmeters 1 and 2 so that it is directed toward Flowmeter 1, so that water from the fluid reservoir tank flows through Flowmeter 1 at the start of the test.
7. If a pressure greater than atmospheric pressure is to be applied to the water surface of the fluid reservoir tank, adjust the pressure applied to the water surface of the fluid reservoir tank. If only atmospheric pressure is used on the water surface of the fluid reservoir tank, then no adjustment can be made.
8. Begin the fluid injection by pressurizing the actuator of the fluid-injection valve using the pressure manifold (see the section “4.5 Fluid-Injection Apparatus” on page 27 for the appropriate pressure to open the fluid-injection valve).
9. Monitor the flow rate from Flowmeter 1, the increase in fluid pressure in the test interval, and any changes in the fluid pressure above or below the test interval. See figure 48 for an example of the time-varying fluid pressure in the test interval and fluid-injection rate during a fluid-injection test.
10. If the flow rate measured on Flowmeter 1 reduces to zero, switch the three-way valve on the plate holding Flowmeters 1 and 2 so that it is directed to Flowmeter 2, and continue to monitor the flow rate and the changes in fluid pressure in the test interval and above and below the test interval.
11. Monitor the flow rate and fluid pressure in the test interval until the rate of change in each is small compared to the magnitude of the response to the fluid injection; usually, fluid-injection tests are conducted for approximately 10 minutes to estimate the transmissivity of the fractures in the test interval in the immediate vicinity of the borehole.

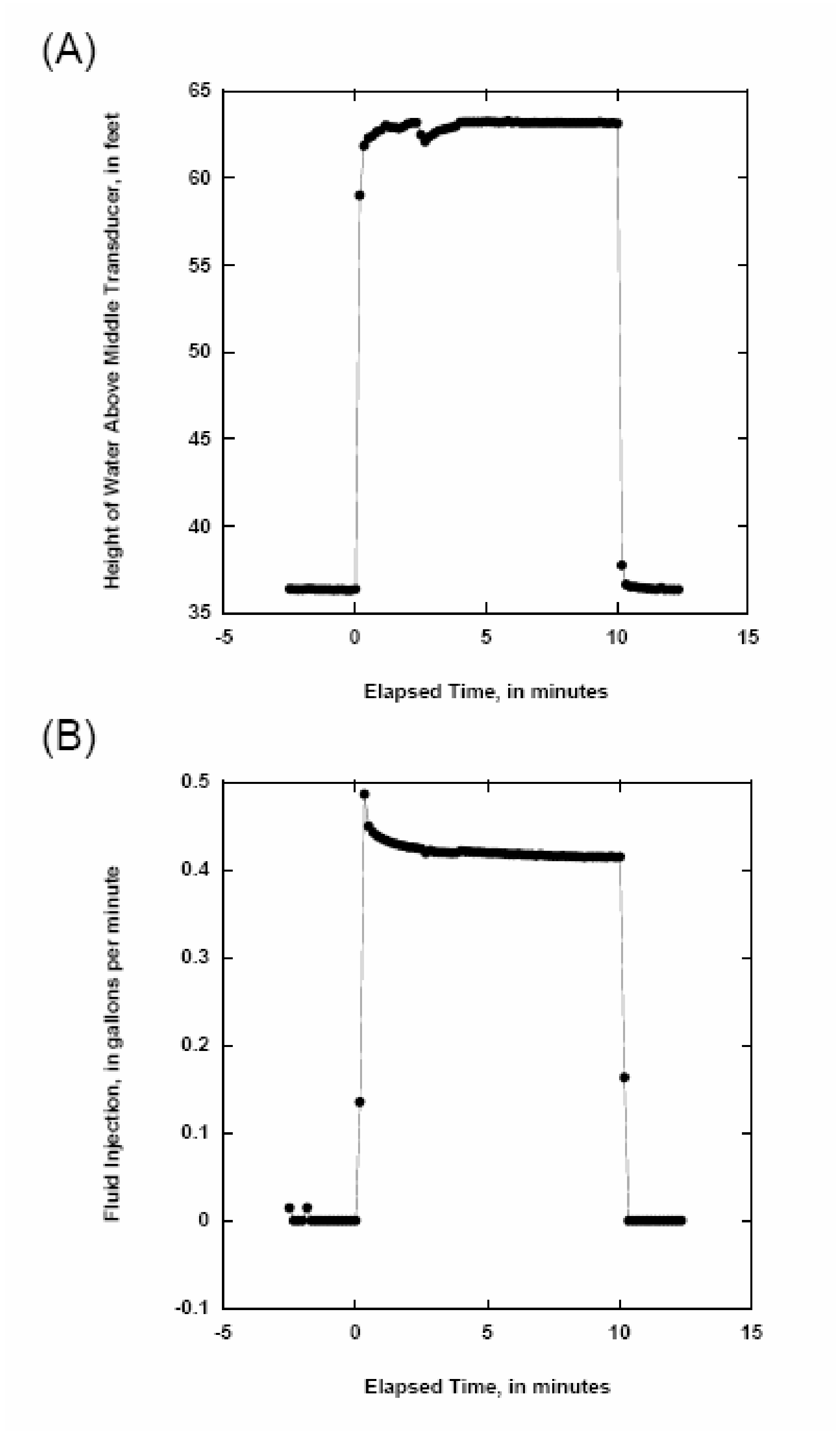

Figure 48. Diagrams of time-varying (A) height of water above the middle-zone transducer and (B) fluid-injection rate for a fluid-injection test conducted with the Multifunction BAT^3 in an isolated interval of Stable Well C at the U.S. Geological Survey Leetown Science Center, Kearneyville, West Virginia, July 2004.

After the flow rate and pressure response in the test interval stabilizes, the injection test in the test interval can be terminated, or another fluid-injection test can be conducted at a different injection rate by changing the air pressure applied to the water surface of the fluid reservoir tank. Fluid-injection tests at different injection rates can only be conducted if the fluid reservoir tank is configured such that a pressure greater than atmospheric pressure can be applied to the water surface of the fluid reservoir tank. If only atmospheric pressure is being applied to the water surface of the fluid reservoir tank, then only one fluid-injection test can be conducted in the test interval.

If another fluid-injection rate is to be applied to the test interval, the following steps are conducted:

12. Adjust the air pressure applied to the water surface of the fluid reservoir tank by using the in-line pressure regulator.
13. If Flowmeter 1 was monitoring the flow rate into the test interval at the end of the previous injection test, repeat steps 9-11 given above.
14. If Flowmeter 2 was monitoring the flow rate into the test interval at the end of the previous injection test, continue to monitor the flow rate in the test interval using Flowmeter 2 and repeat step 11 given above. If the change in the injection rate results in a flow rate that exceeds the upper limit of Flowmeter 2, switch the three-way valve on the plate with Flow Meters 1 and 2 so that it is directed to Flowmeter 1 and then repeat steps 9-11 given above.

After completing one or more fluid-injection tests in the test interval, the fluid-injection test is terminated using the following steps:

15. Reduce the pressure applied to the actuator of the fluid-injection valve to close the valve.
16. Monitor the change in fluid pressure in the test interval until it returns to its pretest condition.

After the completion of the steps listed above, the following steps should be conducted prior to moving the borehole equipment to the next test interval in the borehole:

17. Open the transducer “bleed” valves by applying pressure to the valves through the pressure manifold.
18. Deflate the top and bottom packers to the target pressure for their depth in the borehole.
19. Remove the top-zone transducer from the borehole.

Fluid-injection tests usually take between 15 and 20 minutes to complete the steps noted above for each injection. An estimate of the transmissivity of the test interval can be made from each fluid-injection rate. Using multiple injection rates makes it possible to check the reproducibility of the estimate of the transmissivity of the fractures intersecting the test interval.

Similar to the discussion in the section “10.2 Geochemical Sampling” on page 96, when conducting fluid-injection tests, the fluid pressure should be monitored above and below the test interval using the top- and bottom-zone transducers. Changes in fluid pressure in the top- and bottom-zone pressure transducers could indicate that the packers are not sealing properly at the borehole wall, or that fractures in the test interval are connected to fractures in the formation that intersect the borehole above or below the test interval.

Changes in fluid pressure above or below the test interval that occur immediately at the onset of fluid injection could indicate packers that are not sealing properly along the borehole wall, or the presence of highly transmissive fractures in the test interval that intersect other highly transmissive fractures that intersect the borehole above or below the test interval. Under such conditions, it may not be possible to estimate the hydraulic properties of fractures intersecting the test interval, because the test interval has not been isolated in the borehole. It may be necessary to adjust the length of the test interval by either increasing or decreasing the length of the test interval to isolate a section of the borehole hydraulically.

Fluid pressure changes above or below the test interval that do not occur immediately at the onset of fluid injection may be the result of fluid pressure responses through the network of fractures in the formation that eventually intersect with fractures in the borehole above or below the test interval. The magnitude and timing of pressure responses measured above or below the test interval will play a role in the interpretation of the transmissivity of the test interval. Winston and Shapiro (2007) discuss several hydrogeologic conceptual models for interpreting the fluid pressure responses in the test interval from fluid injection tests.

10.5 Pressurized-Slug Test

Slug tests are commonly used to estimate hydraulic properties of wells in shallow unconsolidated geologic material by adding or displacing a volume of water in the well casing and monitoring the dissipation of that perturbation back to the ambient condition in the well (see, for example, Cooper and others, 1967). Bredehoeft and Papadopulos (1980) extended this method by placing a packer in the casing or the borehole and injecting water below the packer. The interval below the packer is pressurized because there is no free-water surface in the test interval. This method proved to be less time consuming in conducting slug tests in low-permeability formations because the hydraulic response in the borehole is controlled by the compressibility of the fluid rather than volumetric displacement of water (Bredehoeft and Papadopulos, 1980).

The downhole equipment of the Multifunction BAT^3 can conduct pressurized-slug tests in discrete hydraulically isolated intervals of a borehole by injecting a small volume of water into the test interval and monitoring the dissipation of the pressure perturbation back to ambient conditions. Pressurized-slug tests can be conducted in test intervals having low transmissivity that cannot be tested by pumping water because the rate of withdrawal would be below the capacity of most pumps. The configuration of the downhole equipment and the tubing connections for conducting slug tests is identical to that for fluid-injection tests, which are described in the sections “4.7 Connecting Downhole Components” on page 29, “4.9 Connecting Tubing” on page 35, and “4.10 Summary of Cables and Tubing Extending to Land Surface” on page 40. If other types of hydraulic testing are to be coupled with slug tests, the downhole components and tubing of the Multifunction BAT^3 should be configured accordingly.

Prior to conducting a slug in a test interval, an ambient hydraulic head measurement should be made using the procedures given in the section “10.1 Ambient Hydraulic Head” on page 92. If fluid-withdrawal tests are to be conducted and an in-line check valve is located in the pump discharge tubing, the steps given in the section “10.3 Single-Hole Hydraulic Test by Fluid Withdrawal” on page 99 should also be included in preparing the downhole components of the Multifunction BAT^3 once they are lowered in the borehole.

The slug test pressurizes the test interval between the packers by injecting a small volume of water and then monitoring the fluid pressure response to this hydraulic perturbation. For this reason, all mechanical outlets for the water in the test interval must be sealed. Leaking of water from fittings in the test interval will result in erroneous estimates of the hydraulic properties of the test interval. It is also necessary to insure that the fluid injected into the test interval does not exit the discharge tubing from the pump, if the downhole equipment is also configured for pumping. Therefore, in conducting a slug test, it is necessary to cap the end of the pump discharge tubing at land surface with a pressure tight fitting and insure that all fittings in the pump discharge tubing are pressure tight.

It is also recommended that the equipment configuration be tested for leaks by conducting a slug test or fluid-injection test in the surface casing of the borehole. If a sufficient length of the surface casing is not filled with fluid to conduct a slug test between the packers, then a presumed impermeable section of the borehole can be used for this purpose. A log of the borehole walls to identify fractures would be needed to insure that there are no fractures in the test interval; however, borehole scanning logs may not detect all fractures. The results of conducting a slug test in the surface casing or an impermeable section of the borehole should show an initial pressurization of the test interval, because of the compressibility of the fluid and downhole apparatus between the packers; however, because the surface casing is assumed to be impermeable, the pressure should not dissipate back to the ambient fluid pressure in the test interval. If the fluid pressure does dissipate in the test interval when conducting a slug test in the surface casing, then a leak exists in the downhole equipment, and the equipment should be checked to insure that all possible mechanical outlets for water in the borehole apparatus are properly sealed. This would also include placing a pressure-tight fitting on the outlet of the discharge tubing from the downhole pump.

The steps for conducting a slug test are similar to those for conducting a fluid-injection test; however, in a pressurized-slug test, fluid is only briefly injected into the test interval from the fluid reservoir tank at land surface, rather than the continuous injection of fluid in a fluid-injection test. Slug tests are perhaps easier to conduct than fluid-injection tests, because they require less water to inject than fluid-injection tests, and thus, a smaller fluid reservoir tank would be needed. However, slug tests may be more difficult to interpret than fluid-injection tests in estimating the hydraulic properties of the test interval, because the interpretation of slug tests requires the analysis of transient fluid pressure responses in the test interval. In comparison, fluid-injection tests can estimate transmissivity by assuming that a steady-state flow regime has been established; storativity, however, is not estimated from such an assumption. In addition, the estimation of hydraulic properties from slug tests may be sensitive to achieving an ambient hydraulic head prior to the start of the slug test. If the ambient hydraulic head has not been achieved prior to the start of the slug test, flow into or out of the test interval will exist at the onset of the test, which may affect the dissipation of the fluid pressure perturbation and the estimation of the hydraulic properties of the test interval (Neuzil, 1982). In contrast, during fluid-injection tests, the change in fluid pressure and the flow rate induced by fluid-injection tests usually dwarfs small deviations from the ambient fluid pressure and the flow into or out of the borehole prior to the onset of the test.

In general, the interpretation of slug tests to estimate hydraulic properties of the test interval do not require information on the flow rate into the test interval. Usually, slug tests are interpreted from the decaying pressure response from a known change in the fluid pressure in the test interval. In formations with low transmissivity, however, the compressibility of the downhole equipment (tubing and packers) in the test interval may be large relative to the storativity of the formation. Using the transient pressure response in the test interval may result in erroneous estimates of the transmissivity and storativity of the test interval (Neuzil, 1982). Neuzil (1982) describes a method of calculating the compressibility of the downhole equipment from the volume of water injected into the test interval, which can then be used in place of the water compressibility in the method of interpreting pressurized-slug tests given in Bredehoeft and Papadopulos (1980).

After following the procedure to measure the ambient hydraulic head in the test interval, the following steps are performed to conduct a slug test, which includes recording the time at which these steps are conducted (see the section "8.7 Documentation Collected During Borehole Testing" on page 78):

1. Check that the tubing from the fluid reservoir tank is connected to the valve on the plate with Flowmeters 1 and 2, and check that the fluid-injection tubing leading from the fluid reservoir tank to the downhole fluid-injection valve has been purged of air. Also, check that the manual valve at the outlet of the fluid reservoir tank is open.
2. Check that a pressure-tight cap has been placed at the end of the tubing (at land surface) leading from the downhole pump, if the equipment is configured for pumping.
3. Check that the cables from Flowmeters 1 and 2 are connected to the data-acquisition panel, and check that the 12 V DC batteries used to power the flow meters are also connected to the data-acquisition panel. If the cable from Flowmeter A is connected to the data-acquisition panel for fluid-withdrawal tests or geochemical sampling, disconnect this cable from the data-acquisition panel prior to connecting Flowmeters 1 and 2 to the data-acquisition panel.
4. Check that the proper calibrations and conversion values are used in the BAT^3 Analyzer to visualize the responses for Flowmeters 1 and 2.
5. Check that no pressure is applied to the fluid-injection valve at the start of the test, and that Flowmeters 1 and 2 measure a zero flow rate.
6. Move the three-way valve on the plate holding Flowmeters 1 and 2 so that it is directed toward Flowmeter 1, so that water from the fluid reservoir tank flows through Flowmeter 1 at the start of the test.
7. Begin the slug test by pressurizing the actuator of the fluid-injection valve using the pressure manifold (see the section "4.5 Fluid-Injection Apparatus" on page 27 for the proper pressure to open the fluid-injection valve). This opens the fluid-injection valve in the test interval and increases the fluid pressure in the test interval. It may take several seconds for the fluid-injection valve to open because the pressure needs to be increased to open the downhole valve.
8. After the downhole valve is opened and remains open for several seconds, it should be closed, so that the hydraulic perturbation resembles an instantaneous slug of water injected into the test interval.
9. The fluid pressure in the test interval is monitored until the fluid pressure is returned to the ambient pressure prior to the start of the test.

To monitor the initial hydraulic perturbation in the test interval, it will be necessary to increase the frequency at which the data-acquisition apparatus queries the pressure transducers. Measurements once every second should be used to capture the magnitude of the change in the fluid pressure in the test interval at the onset of the slug test. Instructions for changing the sampling interval for the data-acquisition equipment are given in the section “8.4 Changing the Sampling Interval” on page 74. The duration of the slug test will depend on the transmissivity of the formation; however, the duration of slug tests conducted in a fluid-filled interval that is hydraulically isolated by two packers in a borehole will take less time than a slug test conducted in a borehole with a free-water surface (Bredehoeft and Papadopulos, 1980).

After the completion of the steps listed above, the following steps should be conducted prior to moving the borehole equipment to the next test interval in the borehole:

10. Open the transducer “bleed” valves by applying pressure to the valves through the pressure manifold.
11. Deflate the top and bottom packers to the target pressure for their depth in the borehole.
12. Remove the top-zone transducer from the borehole.

Similar to the discussion in the section “10.2 Geochemical Sampling” on page 96, when conducting pressurized-slug tests, the fluid pressure should be monitored above and below the test interval using the top- and bottom-zone transducers. Changes in fluid pressure in the top- and bottom-zone pressure transducers could indicate that the packers are not sealing properly at the borehole wall, or that fractures in the test interval are connected to fractures in the formation that intersect the borehole above or below the test interval.

Changes in fluid pressure above or below the test interval that occur immediately at the onset of fluid injection could indicate packers that are not sealing properly along the borehole wall, or the presence of highly transmissive fractures in the test interval that intersect other highly transmissive fractures that intersect the borehole above or below the test interval. Under such conditions, it may not be possible to estimate the hydraulic properties of fractures intersecting the test interval, because the test interval has not been isolated in the borehole. It may be necessary to adjust the length of the test interval by either increasing or decreasing the length of the test interval to isolate a section of the borehole hydraulically.

Fluid pressure changes above or below the test interval that do not occur immediately at the onset of the slug test may be the result of fluid pressure responses through the network of fractures in the formation that eventually intersect with fractures in the borehole above or below the test interval. The magnitude and timing of pressure responses measured above or below the test interval will play a role in the interpretation of the transmissivity of the test interval.

10.6 Single-Hole Tracer Test by Fluid Injection Followed by Pumping

Properties of the formation that affect chemical transport can be estimated by conducting tracer tests, where a solution with a known mass of a dissolved constituent is injected into the formation. The properties of the formation that affect chemical migration are estimated by interpreting either the spatial distribution of the tracer concentration at a specific time, or the time varying tracer concentration at one or more collection wells. Usually, tracer tests are conducted by inducing the migration of the tracer solution between two wells in the formation by pumping from one well and injecting the tracer solution into an adjacent well (Shapiro and Nicholas, 1989; Becker and Shapiro, 2000). Tracer tests can also be conducted from a single well, by first injecting the tracer solution and then later withdrawing it from the same well (Meigs and Beauheim, 2001;

Haggerty and others, 2001; Altman and others, 2002; Becker and Shapiro, 2003). Under this approach, after completing the injection of the tracer solution in the formation, the tracer is allowed to migrate in the formation under ambient hydraulic conditions for a predetermined period of time, and then later it is pumped from the formation.

10.6.1 General Information

The Multifunction BAT^3 can be used to conduct a single-hole tracer test in discrete intervals of a borehole, where a tracer solution is mixed in the fluid reservoir tank, and injected into the test interval through the fluid-injection valve. The volume of the tracer solution injected into the test interval can be measured by monitoring the flow rate through the fluid-injection tubing using either Flowmeters 1 or 2. A sample of the tracer solution in the fluid reservoir tank can be taken to measure the concentration of the tracer solution. Using the concentration of the tracer solution and the volume of tracer solution injected, the total mass of the tracer that is potentially injected into the formation can be calculated.

Injecting the tracer solution in the test interval between the two packers, however, does not guarantee that the tracer solution has been forced into the formation. Some of the tracer solution is likely to remain in the borehole between the two packers. If the tracer solution resident in the borehole diffuses or is advected out into the formation over time, it may be difficult to estimate formation properties that influence chemical migration from the interpretation of the recovery of the time-varying tracer concentration by later pumping the test interval. Interpretation of the tracer recovery usually requires the explicit knowledge of the time over which the tracer was first injected into the formation, and the total mass of the tracer injected into the formation. Shapiro and Hsieh (1996) developed a borehole apparatus that explicitly controls the delivery of the tracer into the formation. In lieu of using that equipment to conduct tracer tests in boreholes, the injection of the tracer solution into the test interval should be followed by the injection of a tracer-free solution. The injection of the tracer-free solution forces the residual tracer solution in the borehole into the formation.

The need to inject a tracer-free solution into the test interval to force the tracer solution into the formation is similar to the concept that requires the purging of the test interval prior to the collection of water samples for geochemical analyses (see the section “10.2.2 Purging the Test Interval” on page 97). As the tracer solution is injected into the test interval, it mixes with the water resident in the test interval; similarly, the water drawn into the test interval during pumping for geochemical sampling mixes with the water resident in the test interval. Consequently, in conducting tracer tests in the interval, it is advantageous to minimize the length of the test interval. This minimizes the volume of the tracer-free solution that is needed to flush the test interval, which in turn, minimizes the time needed to inject the tracer into the formation. The discussion of purging a sampling interval for geochemical sampling given in Robbins and Martin-Hayden (1991) and Shapiro (2002b) can also be applied to determine the volume of water needed to flush the test interval following the injection of a tracer solution.

After injecting the tracer solution, followed by the tracer-free solution, and allowing the tracer solution to migrate in the formation under ambient conditions, the submersible pump in the test interval is used to recover the tracer solution. If possible, a constant pumping rate should be maintained. The pumping rate is monitored using one of the flowmeters of the Multifunction BAT^3, and the samples of the pumped water should be taken over time to identify the time-varying concentration of the tracer in the pumped water. Using the time-varying tracer concentration and the pumping rate, the total mass of the tracer recovered from the formation can be calculated. Pumping of the test interval and the collection of water samples for the analyses of tracer concentration should continued until the total mass of the tracer recovered from the pumped water approaches an asymptotic limit. In general, the mass of the tracer injected into the formation may not be fully recovered by pumping, because of various physical and chemical properties of the formation.

Properties of the formation that affect chemical migration are estimated from the time-varying concentration of the tracer solution in the pumped water (see, for example, Haggerty and others, 2001; Altman and others, 2002; Becker and Shapiro, 2003). A discussion of the interpretation of such tracer tests to estimate formation properties is beyond the scope of this report. The duration of the tracer injection and the duration of the time when the tracer is allowed to migrate in the formation under ambient conditions can be varied and accommodated in the interpretation of the time-varying tracer concentration in the pumped water.

Prior to conducting a single-hole tracer test in a given test interval, it is advantageous to conduct a hydraulic test first to determine the ability of the fractures in the test interval to accept water during fluid injection, and produce water during pumping. Usually, a tracer test is most easily conducted in test intervals with highly transmissive fractures; however, tracer tests can be conducted in less transmissive fractures. In low-transmissivity fractures tracer tests could require an extended period of time to inject the tracer into the formation, and later recover the tracer by pumping.

Conducting a hydraulic test in the test interval prior to conducting a single-hole tracer test is also advantageous to determine if the location of the packers is suitable for conducting the tracer test. During the hydraulic test, rapid changes in fluid pressure above or below the test interval could indicate that packers are not sealing properly at the borehole wall, or there are highly permeable fractures in the test interval that intersect other highly permeable fractures above or below the test interval (see the section “10.2 Geochemical Sampling” on page 96). Conducting a tracer test under such conditions could result in the tracer solution being forced into the borehole above or below the test interval, rather than into the formation, which would lead to erroneous interpretations of the properties of the formation that affect chemical transport. If hydraulic responses are monitored above or below the test interval, the length of the test interval may need to be adjusted to conduct a successful tracer test in the formation.

10.6.2 Preparing the Fluid Reservoir Tanks

Injecting a tracer solution and then a tracer-free solution into the test interval will require two separate fluid reservoir tanks, one filled with the tracer solution and the other filled with a tracer-free solution. The tubing extending from the outlets of the two fluid reservoir tanks should be connected together using a three-way valve (fig. 49), which, in turn, is connected to the three-way valve on the plate holding Flowmeters 1 and 2. The position of the three-way valve between the two fluid reservoir tanks will dictate which of the fluid reservoir tanks will inject water into the test interval at a given time.

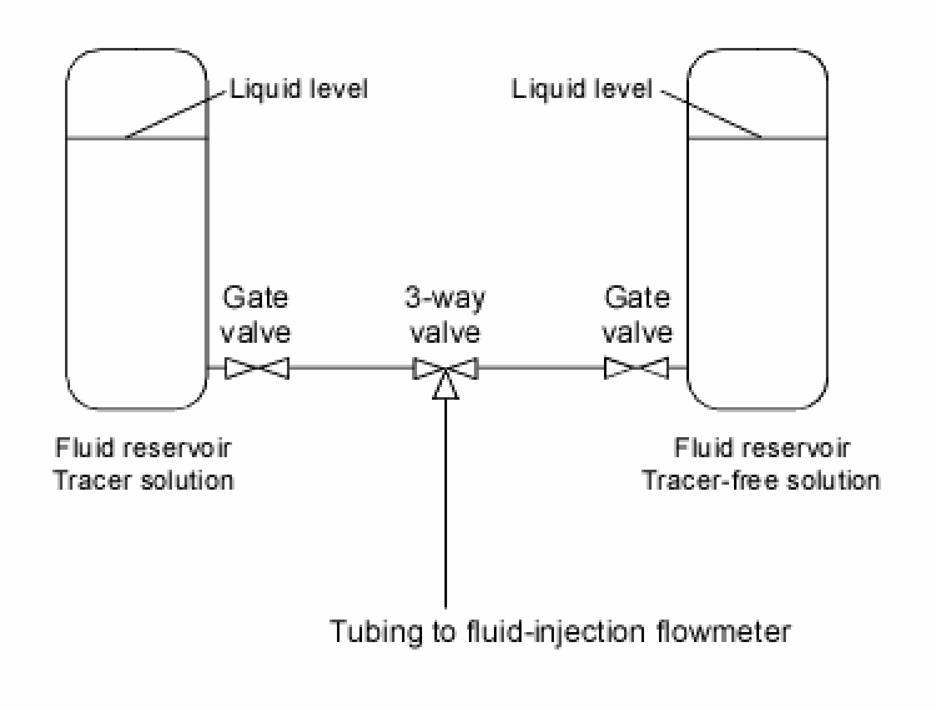

Figure 49. Schematic diagram of the configuration of two fluid reservoir tanks used to inject a tracer solution and a tracer free solution with the Multifunction BAT^3.

In preparing for the injection of the tracer solution and the tracer-free solution, the tubing leading from each fluid reservoir tank should be purged of air. Because two fluid reservoir tanks are connected together, the procedure to purge the air from the fluid-injection tubing will need to be slightly modified from the procedure given in the section “9.3 Preparing the Fluid Reservoir Tank for Fluid Injection” on page 83. The following steps are taken to prepare the fluid reservoir tanks filled with the tracer solution and the tracer-free solution:

1. Fill one fluid reservoir tank with a tracer solution, and the second fluid reservoir tank with a tracer-free solution (see the section “7.7 Fluid Reservoir Tank” on page 67 for details on filling a fluid reservoir tank). Also, collect a water sample for chemical analyses from each tank.
2. Connect tubing from the outlet of the two fluid reservoir tanks to a three-way valve (fig. 49). The length of the tubing between the tanks and the three-way valve should be minimized.
3. Use 0.5-inch-diameter tubing to connect the three-way valve between the two fluid reservoir tanks to the three-way valve on the plate holding Flowmeters 1 and 2.
4. Open the manually operated valve at the outlet of the fluid reservoir tank filled with tracer-free solution. Keep the manually operated valve at the outlet of the fluid reservoir tank filled with the tracer solution closed.
5. Adjust the three-way valve between the two fluid reservoir tanks so that it will allow fluid from the tank with the tracer-free solution to purge the air from the fluid-injection tubing.
6. Follow the procedure given in the section “9.3 Preparing the Fluid Reservoir Tank for Fluid Injection” on page 83 to purge the air from the fluid-injection tubing, that is, use the tracer-free solution to purge the air from the fluid-injection tubing.

7. Check that the downhole fluid-injection valve has been closed and the three-way valve between the two fluid reservoir tanks is still adjusted so that water from the tracer-free solution can flow through the fluid-injection tubing.
8. Check that the water surface of the fluid reservoir tank filled with the tracer solution is open to atmospheric pressure.
9. Open the manually operated valve at the outlet of the fluid reservoir tank filled with the tracer solution, and open a fitting above the water surface in the tank so that the water surface in the tank is open to atmospheric pressure. The air in the tubing between the outlet valve and the three-way valve between the two fluid reservoir tanks will move up into the tank and discharge at the water surface in the tank. The outlet valve can be left open and the pressure tight fitting at the top of this fluid reservoir tank can be connected to a pressure source, if a pressure above atmospheric pressure is to be applied to the water surface of the tracer solution in the fluid reservoir tank.

10.6.3 Procedure

The Multifunction BAT^3 can be used to conduct a single-hole tracer test by first injecting a tracer solution into the test interval, then flushing the test interval with tracer-free water, and later pumping the test interval to recover the tracer. The downhole components of the Multifunction BAT^3 are configured to conduct both fluid-injection and fluid-withdrawal tests. The configuration of the downhole equipment and the tubing connections for conducting both fluid-injection tests and fluid withdrawal are given in the sections “4.7 Connecting Downhole Components” on page 29, “4.9 Connecting Tubing” on page 35, and “4.10 Summary of Cables and Tubing Extending to Land Surface” on page 40. In addition, an in-line check valve should be placed in the pump discharge tubing (see the section “4.9.4 Pump Discharge - Water Line” on page 37). Prior to initiating a single-hole tracer test in the test interval, the discharge tubing from the pump should be filled with water, and an ambient hydraulic head measurement should be made using the procedures given in the sections “10.1 Ambient Hydraulic Head” on page 92 and “10.3 Single-Hole Hydraulic Test by Fluid Withdrawal” on page 99.

The injection of the tracer solution and the tracer-free solution pressurizes the test interval between the packers. To insure that there is an accurate measure of the tracer mass that is injected into the formation, all mechanical outlets for the water from the fluid reservoir tank, other than the fluid-injection valve in the fluid-injection apparatus must be sealed. For example, it is extremely important that the fittings used to connect the fluid-injection tubing from the fluid-injection tank down to the fluid injection valve be pressure tight so that the tracer solution does not leak from these fittings. The leaking of water from any of these fittings will result in erroneous estimates of the tracer mass injected into the test interval. It is also necessary to insure that the fluid injected into the test interval does not exit the discharge tubing from the pump. Therefore, it is also necessary to cap the end of the pump discharge tubing at land surface with a pressure tight fitting and insure that any fitting in the pump discharge tubing are pressure tight.

It is recommended that the fluid-injection equipment be tested for leaks by conducting a test in the surface casing of the borehole. If a sufficient length of the surface casing is not filled with fluid to conduct a fluid-injection test between the packers, then a presumed impermeable section of the borehole can be used for this purpose. A log of the borehole walls to identify fractures would be needed to insure that there are not fractures in the test interval; however, borehole scanning logs may not detect all fractures. During the testing of the fluid-injection apparatus, the fluid from the reservoir tank holding the tracer-free water should be used. Additional information about conducting a test of the fluid-injection apparatus is given in the section "10.4 Single-Hole Hydraulic Test by Fluid Injection" on page 102.

The procedure for injecting a tracer solution from the fluid reservoir tank is similar to the procedure for conducting a fluid-injection test (see the section "10.4 Single-Hole Hydraulic Test by Fluid Injection" on page 102). Instead of allowing the flow rate and fluid pressure to equilibrate during injection, the injection of the tracer solution should be conducted over a predetermined period of time to inject a prescribed mass of the tracer. After following the procedure to measure the ambient hydraulic head in the test interval, the following steps are performed to conduct a tracer test, which includes recording the time at which these steps are conducted (see the section "8.7 Documentation Collected During Borehole Testing" on page 78):

1. Check that the tubing from the fluid reservoir tanks (filled with tracer solution and tracer-free solution) are connected together using a three-way valve, and the outlet from this valve is connected to the plate with Flowmeters 1 and 2 (fig. 49). Check that the fluid-injection tubing leading from the fluid reservoir tanks to the downhole fluid-injection valve has been purged of air (see the sections "9.3 Preparing the Fluid Reservoir Tank for Fluid Injection" on page 83 and "10.6.2 Preparing the Fluid Reservoir Tanks" on page 111). Also, check that the manual valves at the outlets of the fluid reservoir tanks are open, and the three-way valve between the two fluid reservoir tanks is initially directed toward the fluid reservoir tank with the tracer-free solution.
2. Check that a pressure-tight cap has been placed at the end of the tubing (at land surface) leading from the downhole pump.
3. Check that the cables from Flowmeters 1 and 2 are connected to the data-acquisition panel, and check that the 12 V DC batteries used to power the flow meters are also connected to the data-acquisition panel. If the cable from Flowmeter A is connected to the data-acquisition panel for fluid-withdrawal tests or geochemical sampling, disconnect this cable from the data-acquisition panel prior to connecting Flowmeters 1 and 2 to the data-acquisition panel.
4. Check that the proper calibrations and conversion values are used in the BAT^3 Analyzer to visualize the responses for Flowmeters 1 and 2.
5. Check that no pressure is applied to the fluid-injection valve at the start of the test, and that Flowmeters 1 and 2 measure a zero flow rate.
6. Move the three-way valve on the plate holding Flowmeters 1 and 2 so that it is directed toward Flowmeter 1, so that water from the fluid reservoir tank flows through Flowmeter 1 at the start of the test.
7. If a pressure greater than atmospheric pressure is to be applied to the water surface of the fluid reservoir tanks, adjust the pressure applied to the water surface of the fluid reservoir tanks. If only atmospheric pressure is used on the water surface of the fluid reservoir tank, then no adjustment can be made.
8. Turn the three-way valve between the two fluid reservoir tanks so that it will allow fluid from the tank filled with the tracer solution into the fluid-injection tubing.
9. Begin the injection of the tracer solution by pressurizing the actuator of the fluid-injection valve using the pressure manifold (see the section "4.5 Fluid-Injection Apparatus" on page 27 for the appropriate pressure to open the fluid-injection valve).

10. Monitor the flow rate from Flowmeter 1, the increase in fluid pressure in the test interval, and any changes in the fluid pressure above or below the test interval.
11. If the flow rate measured on Flowmeter 1 reduces to near zero, switch the three-way valve on the plate holding Flowmeters 1 and 2 so that it is directed to Flowmeter 2, and continue to monitor the flow rate and the changes in fluid pressure in the test interval and above and below the test interval.
12. At a predetermined time, stop the injection of the tracer solution and begin the injection of the tracer free-solution by switching the three-way valve between the two fluid reservoir tanks so that it now allows water from the tank filled with tracer-free solution to enter the fluid-injection tubing.
13. At a predetermined time, stop the injection of the tracer-free solution by reducing the pressure applied to the actuator of the downhole fluid-injection valve.
14. Water samples for chemical analyses should be taken from the two fluid reservoir tanks for comparison with the analyses of water samples taken from these tanks at the start of the tracer injection.

The duration of the tracer injection will depend on the mass of the tracer that is intended to be injected into the formation. Also, the duration of the injection from the fluid reservoir tank filled with tracer-free water will depend on the volume of water between the packers and the hydraulic properties of the formation. Following the injection of the tracer-free solution, the tracer in the formation is allowed to migrate for a predetermined time (see, for example, Haggerty and others, 2001; Altman and others, 2002; Becker and Shapiro, 2003). During this time, the following steps are used to prepare the data-acquisition equipment to monitor the pumping of the test interval during the recovery the tracer solution:

15. The discharge tubing leading from the submersible pump in the test interval should be connected to the appropriate flowmeter (Flowmeter A or Flowmeter 1) to monitor the pumping rate during the recovery of the tracer injected into the formation. The outlet from the flowmeter should be capped with a pressure-tight fitting until the start of pumping.
16. The cable from the flow meter used to monitor pumping should be connected to the data-acquisition panel and the proper calibrations and conversion values should be used in the BAT^3 Analyzer to visualize the responses of the flowmeter.
17. Fluid pressures in the test interval and above and below the test interval should continue to be monitored during the migration of the tracer in the formation.

After the predetermined time for the tracer to migrate in the formation, the following steps are conducted to recover the tracer by pumping the test interval:

18. Remove the pressure-tight cap from the end of the tubing leading from the submersible pump in preparation for pumping and the collection of water samples for chemical analyses. The collection of water samples should be conducted after the flowmeter that is used to monitor the pumping rate, to insure that an accurate pumping rate is recorded.
19. Turn on the pump using the (red) on/off switch on the Grundfos power converter, and adjust the pumping rate using the variable speed control dial on the Grundfos power converter.

Experience from hydraulic tests previously conducted in the test interval should be used to identify the appropriate pumping rate during the recovery of the tracer from the formation.

20. Monitor the pumping rate, and the fluid pressures in the test interval, and above and below the test interval.
21. Monitor the concentration of the tracer from the discharge water over time and calculate the mass of the tracer recovered from the formation using the pumping rate and the time-varying concentration.
22. When the mass of the tracer recovered approaches an asymptotic limit, the pumping of the test interval can be terminated by turning off the pump using the (red) on/off switch on the Grundfos power converter. To determine if an asymptotic limit of the tracer mass has been recovered, the logarithm of the tracer concentration should be plotted versus the logarithm of time from the start of pumping (see, for example, Shapiro, 2002b, and Becker and Shapiro, 2003).
23. Monitor the fluid pressures in the test interval, and above and below the test interval after the termination of pumping until fluid pressure responses have equilibrated.

After the completion of the pumping to recover the tracer from the formation, the following steps should be conducted prior to moving the borehole equipment to the next test interval in the borehole:

24. Open the transducer “bleed” valves by applying pressure to the valves through the pressure manifold.
25. Deflate the top and bottom packers to the target pressure for their depth in the borehole.
26. Remove the top-zone transducer from the borehole.

10.7 Applications Using a Single Packer

In some instances, it may be advantageous or necessary to conduct hydraulic testing or geochemical sampling with only one of the packers inflated. For example, if hydraulic tests or geochemical sampling is to be conducted on fractures near the bottom of the borehole, inflating the bottom packer may interfere with some fractures. Also, if large sections of the borehole need to be tested, inflating only one of the packers will divide the borehole into two intervals, above and below the inflated packer. Large intervals of the borehole may need to be tested based on hydrogeologic reasoning, or if suitable locations cannot be identified for the placement of both packers in the borehole.

Each packer of Multifunction BAT^3 is operated separately. Thus, one packer can be inflated to seal against the borehole wall, whereas the other packer can be left uninflated. If one of the packers is left uninflated, it is recommended that the pressure applied to that packer be equal to the ambient fluid pressure at its depth in the borehole (see the section “9.4 Lowering the Downhole Components in a Borehole” on page 84). Inflating one packer will divide the borehole into two hydraulically separated intervals, above and below the inflated packer. If the top packer is inflated and the bottom packer is not inflated, the test interval is from the bottom of the top packer to the bottom of the borehole. If the bottom packer is inflated, and the top packer is not inflated, the test interval is from the top of the bottom packer to the water surface in the borehole.

All of the procedures discussed previously for testing in boreholes using the Multifunction BAT^3 can be conducted with only one of the packers inflated. If the configuration of the equipment has the top packer inflated, then the test interval does not have a free-water surface, and hydraulic responses in the fluid-filled interval below the top packer would respond similarly to tests conducted in a test interval with both the top and bottom packer inflated. If the test interval below the top packer has many fractures, then problems encountered during testing in long open intervals of bedrock boreholes may be encountered in this configuration of the downhole components of the Multifunction BAT^3; several of these problems are discussed in the “1. Introduction” on page 2.

If only the bottom packer is inflated, the test interval will have a free-water surface. Depending on the local hydrologic conditions and the design of the surface casing in the borehole, the free-water surface may be in the surface casing of the borehole, or in the interval of the borehole open to the formation. With a free-water surface in the test interval, hydraulic responses during testing by withdrawing or injecting fluid will be different from hydraulic responses in a pressurized section of the borehole with no free-water surface. To change the hydraulic head in a borehole with a free-water surface, the water level in the borehole must be raised or lowered, which requires a larger volume of fluid than raising or lowering the hydraulic head in a fluid-filled section of the borehole isolated by two packers (see, for example, Bredehoeft and Papadopulos, 1980). Consequently, larger volumes of fluid may be needed to conduct fluid-injection tests and slug tests, resulting in the rapid draining of the fluid reservoir tank. Unless the interval of the borehole with a free-water surface has a low transmissivity, fluid-injection and slug tests are not recommended; instead, fluid-withdrawal tests should be conducted.

In the interpretation of the hydraulic responses in a test interval to estimate hydraulic properties of the formation, the fluid storage in the test interval must be properly considered. In a pressurized section of the borehole (without a free-water surface), the fluid storage in the borehole is controlled by the fluid compressibility and the compressibility of the borehole equipment. In a test interval with a free-water surface, the fluid storage in the borehole is controlled by the dimensions of the borehole. The BAT^3 Analyzer is designed to interpret hydraulic responses of the test interval and provide estimates of hydraulic properties. The BAT^3 Analyzer can be applied in cases where the test interval is pressurized or has a free-water surface. Additional information on the estimation of hydraulic properties of the test interval is given in the description of the BAT^3 Analyzer (Winston and Shapiro, 2007).

11. Estimating Hydraulic Properties of Test Intervals

Measurements of flow rate and fluid pressure from hydraulic tests are used to estimate hydraulic properties of the test interval. The BAT^3 Analyzer (Winston and Shapiro, 2007) has the capability of performing interpretations on the measured hydraulic data as testing is being conducted with the Multifunction BAT^3. The documentation of the BAT^3 Analyzer includes a detailed discussion of the underlying assumptions for estimating hydraulic properties from single-hole hydraulic tests, such as those conducted with the Multifunction BAT^3, and the assumptions underlying the various hydrogeologic conceptual models that can be used to estimate hydraulic properties of the test interval. A detailed discussion of these topics is not provided in this document and the user is referred to the documentation of the BAT^3 Analyzer for the interpretation of hydraulic tests and the estimation of hydraulic properties from the various types of hydraulic tests.

12. Range Of Estimates of Transmissivity

The sensitivity of the data-acquisition equipment used in the Multifunction BAT^3 dictates the range of the transmissivity that can be resolved by the methods of estimating hydraulic properties. For example, fluid-injection tests or pressurized-slug tests are used to estimate the hydraulic properties of fractures in test intervals with low transmissivity. The minimum flow rate that can be measured with Flowmeter 2 of the Multifunction BAT^3 during fluid-injection testing is approximately 0.001 gal/min. Using the assumption of two-dimensional radial flow in the fractures intersecting the test interval and a spatially uniform transmissivity, the transmissivity of the test interval can be estimated from the Thiem equation (Bear, 1979),

$$h_w = H_0 + \left(\frac{Q}{2\pi T}\right) \ln\left[\frac{R}{r_w}\right] \tag{5}$$

where h_w is the hydraulic head in the test interval after achieving a steady-state flow regime, H_0 is the initial hydraulic head in the test interval at the start of the test, Q is the fluid-injection rate after achieving a steady-state flow regime, r_w is the radius of the borehole in the test interval, T is the transmissivity of the test interval, ln is the natural logarithm, and R is the radius from the borehole at which there is a negligible change in the hydraulic head in the formation; R is also referred to as the radius of influence. Equation (5) can be rearranged to solve for the transmissivity of the test interval, where the parameters h_w, H_0, Q, and r_w are either known or measured, and the magnitude of R is assumed. The radius of influence for the fluid-injection test is unknown because measurements of fluid pressure at distances from the test interval are not made during a single-hole test. The radius of influence, however, appears in the natural logarithm function. Consequently, small changes in R will not affect the estimate of the transmissivity; only order of magnitude changes in R will greatly affect the estimate of the transmissivity. The choice of the radius of influence for the fluid-injection test is dependent on the hydrogeologic conditions. Shapiro and Hsieh (1998) used a radius of influence of approximately 10 ft in the interpretation of fluid-injection tests conducted in igneous and metamorphic rock.

For the lowest measurable flow rate associated with Flowmeter 2, and assuming that the radius of influence is two orders of magnitude larger than the well radius, and assuming a change in the hydraulic head in the test interval on the order of 100 ft due to the fluid injection, the resultant transmissivity is approximately 10^{-3} ft^2/day. Other conditions may result in estimates of the transmissivity that are lower than 10^{-3} ft^2/day.

The maximum transmissivity that can be resolved using the Multifunction BAT^3 can also be estimated by making use of the assumption of steady-state flow and Equation (5). For example, if the maximum pumping rate associated with the Multifunction BAT^3 is assumed to be 2.5 gal/min, and the radius of influence is two orders of magnitude larger than the well radius, then for an assumed change in hydraulic head in the test interval equal to 0.05 ft, the resultant transmissivity is approximately 10^4 ft^2/day. Other conditions may result in estimates of the transmissivity that are larger than 10^4 ft^2/day. Consequently, in the current configuration of the equipment and sensors associated with the Multifunction BAT^3, it is possible to resolve transmissivity of the test interval over 7 orders of magnitude.

13. Removing the Downhole Equipment From the Borehole

When hydraulic testing and geochemical sampling is completed in a borehole, or if the configuration of the equipment needs to be changed for further testing in a borehole, the downhole components of the Multifunction BAT^3 need to be removed from the borehole. To remove the downhole components from the borehole, each packer should be deflated to the ambient fluid pressure for its depth below the water surface in the borehole (see the section "9.4 Lowering the Downhole Components in a Borehole" on page 84). The top and bottom packers may require different pressures if the downhole components are configured with the packers separated by large distances. The gas pressure applied to the packers will need to be adjusted as the downhole components are raised in the borehole.

As the downhole components are raised in the borehole, the tubing connected to the pump and the downhole fluid-injection valve, the tubing used to inflate packers and operate downhole valves, and the electrical cables from the pump and the transducers should be held taught to avoid it from becoming tangled with the downhole components in the borehole. As the tubing is removed from the borehole it should be configured on the ground so that if there is s sudden drop in the downhole components when they are in the borehole, the sudden movement of the tubing and cables at land surface would not result in injury to the equipment operators.

In instances where the fluid in the borehole contains contaminants, it will be necessary to clean the downhole components and the electrical cables attached to the pump and the transducers. When removing the downhole components of the Multifunction BAT^3, including the electrical cables and tubing, the appropriate equipment and supplies for cleaning the equipment and containing the contaminants should be available. Certain types of tubing can also be cleaned; however, if the tubing has been in contact with contaminated water, and it cannot be cleaned, it should be disconnected from the downhole components and discarded properly. Furthermore, if the pump has been used to pump water from the borehole, where the water is suspected of being contaminated, equipment and supplies for flushing the pump should be available, and the quality of the water discharged from the pump should be checked after this procedure.

When the borehole components of the Multifunction BAT^3 are raised above the top of the surface casing in the borehole, the equipment should be removed using procedures similar to its installation in the borehole (see the section "9.4 Lowering the Downhole Components in a Borehole" on page 84). If the apparatus used to hoist the downhole components of the Multifunction BAT^3 is tall enough to raise the entire length of the downhole components, then the equipment can be raised out of the borehole as one unit and lowered to the ground. If the downhole equipment has been in contact with contaminated fluids in the borehole, supplies and equipment should be available to contain contaminated fluids and clean the downhole equipment. When lowering the downhole equipment from its vertical orientation and laying it horizontally on the ground, support should be provided at each of the union ball fittings that connect the various downhole components, as these will be the locations of greatest stress. If the union ball fittings are not supported when the equipment is lowered to the ground, the fittings or equipment could be damaged or broken from the flexure applied to the equipment.

If the apparatus used to raise the downhole components of the Multifunction BAT^3 is not tall enough to raise the entire length of the downhole components out of the borehole, then the downhole components and the tubing will need to be disconnected as they are raised out of the borehole. The downhole components can be disconnected at the union ball fittings. The union ball fittings connecting the transducer shrouds, the top packer, and the pump shroud, however, must remain connected until these components are on the ground, because the pump cable is threaded through these components. If union ball fittings are contained in equipment that is lowered to the ground, support should be provided at the union ball fittings to reduce the stress acting on these connections.

14. Moving the Downhole Equipment to Another Borehole

The downhole components of the Multifunction BAT^3 do not have to be completely dismantled if the equipment needs to be transferred for use in a nearby borehole. If the downhole components of the Multifunction BAT^3 are too long to be hoisted out of the borehole intact, the downhole equipment will need to be disassembled, transported, and then assembled as it is lowered into the borehole.

The downhole components of the Multifunction BAT^3 that are connected with union ball fittings should be properly supported when this equipment is transported. A support should be applied at each of the union ball fittings to reduce the stress applied on these joints in the equipment.

Prior to moving the downhole components to a nearby borehole, tubing and cables should be disconnected from the uphole components, and the uphole components of the Multifunction BAT^3 should be repacked in their packing crates, as some of these instruments are delicate and could be damaged in transport. In particular, the data-acquisition panel, the pressure manifold, the panel of batteries, and the plates containing flowmeters and the in-line pressure regulator should be repacked in their packing crates. In addition, tubing should be disconnected from the sources of compressed gas and the fluid reservoir tank. Depending on the volume and size of the fluid reservoir tank, it may be necessary to drain the water from the tank prior to moving it.

15. Repacking Equipment

If the downhole equipment of the Multifunction BAT^3 was in contact with ground water containing contaminants, decontamination procedures should be applied to the downhole components, including the transducer and pump cables. In addition, the submersible pump and the stainless steel tube that routes water from the pump through the top packer should be flushed to insure that contaminants from the ground water in the borehole are not retained on the equipment. Because the tubing for the Multifunction BAT^3 is the responsibility of the user, the user must decide at the completion of borehole testing whether the tubing should be discarded, or if decontamination can be applied to the tubing so that it can be used again in the future.

At the completion of testing, and after the downhole components of the Multifunction BAT^3 have been removed from the borehole, the tubing should be disconnected from the various components. This includes the tubing extending from the downhole components to the pressure manifold and the flowmeters, as well as the tubing connections in the test interval. In addition, the transducer cables should be disconnected from the data-acquisition panel, and the pump cable should be disconnected from the Grundfos power converter. The transducer cables, including the top-zone transducer that is not connected to the downhole components, should be coiled in a similar manner to that shown in figures 4 and 12. The pump cable also should be rewound on the pump reel.

In preparation for repacking the data-acquisition and downhole-control equipment, tubing should be disconnected from the pressure manifold, the flowmeters, and the in-line pressure regulator. If contaminated ground water was pumped through one or more of the flowmeters, those flowmeters should be subject to decontamination procedures. Furthermore, cables from the flowmeters and batteries should be disconnected from the data-acquisition panel after data acquisition has been stopped (see the section “8.2 Terminating the Connection to the Data Logger” on page 73), and the laptop computer should be disconnected from the Campbell Scientific CR23X data logger.

The data-acquisition and downhole-control equipment are to be packed in Boxes 3, 4 and 5 (fig. 6, 7 and 8). The pressure manifold, the Grundfos power converter for the submersible pump, and the electric water-level monitoring device should be repacked in Box 3. If necessary, decontamination procedures should be applied to the cable and sensor of the electric water-level monitoring device, and it should be allowed to air dry prior to repacking it. The plates holding the flowmeters can be repacked in Box 4 (fig. 7). Prior to repacking the plates with the flowmeters, the plates should be tilted so that any excess water is allowed to drain out of the flowmeters. Also, after draining the flowmeters of water, the flowmeters should be allowed to air dry prior to packing them in the box. Finally, the data-acquisition panel, the battery panel, and the AC adapters for charging the 12 V DC batteries should be repacked in Box 5 (fig. 8).

In preparation for repacking the downhole components of the Multifunction BAT^3, once the downhole components are on the ground, the nut on each union ball fitting should be unscrewed. This will separate the transducer shrouds from the top packer, the top packer from the pump shroud, the pump shroud from the fluid-injection shroud, the fluid-injection shroud from the extension pipe, and the extension pipe from the bottom packer. The union ball fitting should be removed from the extension pipe and packed in Box 1 along with the wrenches used to loosen the nuts on the union ball fittings. The fluid-injection shroud and the bottom packer should be placed in Box 2 (fig. 5). If the swivel-eye hoisting plug and the pressure regulator for cylinders of compressed gas were used, these items should also be packed in Box 2. Two people will need to lift the bottom packer and place it in the shipping box. A discussion of the proper procedure for lifting the packer is given in the section “4.1 Unpacking Downhole Components” on page 16. Both the bottom packer and the fluid-injection shroud should be allowed to air dry before closing the shipping box.

To repack the transducer shrouds, the top packer and the pump shroud in Box 1, the Crouse-Hinds connectors must be loosened on both ends of the stainless steel tube that runs through the top packer and houses the pump cable. Loosening the Crouse-Hinds connector allows the pump cable to be moved through the stainless-steel tube in the packer. Approximately 8 inches of excess pump cable should be pulled through the stainless tube and positioned between the top packer and the pump shroud. Approximately 8 inches of excess pump cable should also be pulled through the transducer shrouds and positioned between the bottom of the transducer shrouds and the top of the top packer. The rubber grommets on the pump cable that are positioned to avoid the cable rubbing against the top and bottom plates of the transducer shrouds will have to be moved as the cable is adjusted between the pump shroud, the top packer, and the transducer shrouds. The excess pump cable that is positioned at these two locations allows the transducer shrouds and the pump shroud to rotate so that they can be packed in their specific compartments without damaging the pump cable.

The procedure given in the section “4.1 Unpacking Downhole Components” on page 16 for unpacking the top packer, the transducer and pump shrouds, and the transducer and pump cables can be used to repack these components by applying the procedure in the reverse order. The transducer shrouds, the top packer, the pump shroud, the transducer cables, and the pump cable and reel should positioned beside Box 1 in the configuration shown in figure 11. The transducer cables should be coiled and the pump cable should be rewound on the pump reel. Two people will be needed to lift the equipment into the shipping box to avoid damage to the equipment and injury to the equipment operators (see the discussion in the section “4.1 Unpacking Downhole Components” on page 16).

Once the top packer, the transducer and pump shrouds, and the transducer and pump cables are repacked in Box 1, the pump cable should be positioned in the existing notches between the compartments to avoid damage to the cable when the lid of the box is closed. The transducer cables should be rewound and placed in the appropriate location in Box 1 (fig. 4) so that when the lid of the box is closed, the transducer cables are not crimped or damaged. Also, the equipment should be allowed to fully dry prior to closing the box.

16. Cautions in Using the Downhole Equipment

The safe operation of the Multifunction BAT^3 requires knowledge and familiarity with the interpretation of borehole geophysical logs, the operation of the equipment needed to raise and lower the downhole components, the operation of the mechanical components of the Multifunction BAT^3, and the safe configuration of the uphole components and tubing. In the description of the components, assembly and operation of the Multifunction BAT^3 given earlier in this report, many safety issues have been addressed. The following paragraphs are intended as a summary of many of the safety concerns the user of the Multifunction BAT^3 should be aware of in operating the equipment.

The safe operation of the Multifunction BAT^3 requires the proper placement of the packers in the borehole for hydraulic testing and geochemical sampling (see the section “7.1 Borehole Geophysical Logs” on page 62). The Multifunction BAT^3 is designed for use in 6-inch-diameter boreholes, and information on borehole conditions, in particular, borehole diameter and the location of fractures, is needed prior to deploying the downhole components in a borehole for hydraulic tests or geochemical sampling. The user of the Multifunction BAT^3 should be familiar with interpreting borehole geophysical logs for discerning borehole diameter and fracture locations. Keys (1988), Keys and MacCary (1983), Hearst and others (2000), and Williams and Johnson (2000) discuss the interpretation of caliper logs and borehole wall-imaging logs.

The downhole components of the Multifunction BAT^3 weigh several hundred pounds and will require a cable and winch, or steel pipe to raise or lower them in a borehole. The user of the Multifunction BAT^3 should be familiar with the operation of the hoisting equipment to avoid injury. In general, it is recommended that two people be involved in the setup and operation of the Multifunction BAT^3, including the use of the hoisting equipment. Also, it is recommended that steel pipe be used to raise and lower the downhole components of the Multifunction BAT^3. In the event that the downhole equipment becomes lodged in the borehole, a cable only offers the opportunity to pull on the equipment to dislodge it, whereas steel pipe can be used to push and apply torque to the downhole equipment. In addition, it is recommended that proper personal safety equipment be used, such as hard hats, gloves, steel-toed boots, and other personal safety equipment that is called for if the formation water contains contaminants.

Because of the weight of the equipment and the fact that the downhole components have tubing and cables extending up the borehole to land surface, the sudden lowering of the equipment in the borehole will drag tubing and cables at land surface down the borehole. The tubing and cables extending out of the borehole and connected to the various uphole components of the Multifunction BAT^3 should be configured on the ground adjacent to the borehole in a manner that will not result in injury to the operators of the equipment in the event that there is a sudden downward movement of the downhole components. If the tubing and cables need to be sanitized prior to their deployment in the borehole and are placed on plastic sheeting, the tubing and cables should be arranged in a manner that will not cause injury to the operators if there is a sudden drop in the downhole components. In addition, it is recommended that the tubing and cables extending down the borehole be held taught when raising or lowering the equipment in the borehole. If the tubing and cables in the borehole are left slack, they could become tangled in the downhole components, which may cause damage to the tubing and result in the equipment becoming stuck in the borehole or operating incorrectly.

Pressurized gases from either a compressor or cylinders are used to operate downhole valves and the packers. It is important that the operator of the Multifunction BAT^3 be familiar with the safe operation of the source of the pressurized gas. It is also important that fittings or tubing that have been filled with pressurized gas first be reduced to atmospheric pressure before any of the fittings are loosened. If gas pressures in tubing are greater than atmospheric pressure, loosening the fittings could result in the fittings and tubing turning into projectiles because of the gas pressure in the tubing. The pressure manifold is equipped with three-way valves that can vent excess pressure in the tubing leading to the various downhole components and the pressure source. If a pressure greater than atmospheric pressure is used on the water surface of the fluid reservoir tank for fluid-injection tests, then a similar type of three-way valve should be used to vent the excess pressure from the fluid reservoir tank, when such an operation is needed (see the sections “7.7 Fluid Reservoir Tank” on page 67 and “9.3 Preparing the Fluid Reservoir Tank for Fluid Injection” on page 83).

The operation of the downhole components of the Multifunction BAT^3 requires the application of compressed gas to downhole valves and packers. It is very important that the tubing leading from land surface to these components be properly marked to avoid the misapplication of compressed gas. Applying compressed gas to one component when it is intended for another component could result in damage to the downhole equipment, which may also result in the equipment becoming stuck in the borehole. The tubing leading from the downhole components of the Multifunction BAT^3 should be labeled prior to lowering the downhole components in the borehole (see the section “5.7 Summary of Connections to Data-Acquisition and Downhole-Control Equipment” on page 58).

Weather conditions should also be considered in the safe operation and care of the components of the Multifunction BAT^3. The data-acquisition equipment should not be exposed to moisture or precipitation. Also, during testing conducted in temperatures that fall below freezing, water should be evacuated from all tubing and tanks that remain at land surface. This includes the fluid-injection tank, the tubing connected to the fluid injection apparatus, the tubing connected to the downhole submersible pump, and the tubing on the plates that house the flowmeters. The tubing that connects to the flowmeters should be detached, and the stainless-steel tubing at the inlets and outlets of the flow meters should be drained of water. In addition, the top-zone pressure transducer should be inspected to insure that no water is in contact with the pressure sensor. In the event that air temperatures drop below freezing, the pressure sensor could be damaged if the water freezes.

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