



BAT³ Analyzer: Real-Time Data Display and Interpretation Software for the Multifunction Bedrock-Aquifer Transportable Testing Tool (BAT³)

By Richard B. Winston and Allen M. Shapiro

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Contents

Abstract.....	1
Introduction	1
Overview of the BAT ³ Analyzer	3
Installing and Starting the BAT ³ Analyzer	4
Windows, Menus, and Icons.....	5
Opening and Saving Data Files	8
Data Display Window	9
Updating Data During Testing	10
Sensor Windows	11
Temperature	11
Barometric Pressure.....	12
Downhole Transducers	12
Flow Rate.....	12
Formatting the Time Axis on Charts	13
Zooming and Panning Charts	13
Formatting Other Chart Attributes	14
Saving and Printing Chart Images.....	14
Applying Calibrations to Raw Data.....	15
Saving and Loading a Conversion Setup File	18
Creating, Saving, and Loading a Calibration Library.....	18
Units Conversion Calculator	20
Calibrating Sensors.....	21
Example of Calibrating a Transducer.....	24
Estimating Hydraulic Properties of a Test Interval.....	25
Example of Estimating Hydraulic Properties of a Test Interval.....	31
Predicting Hydraulic Responses	37
Acknowledgments.....	37
References Cited	38
Appendix 1: File Structure of the Raw Data File (*.dat).....	40
Example	40
Appendix 2: File Structure fo the Interpreted Data File (*.idf).....	41
Example	42
Appendix 3 : Conversion Setup File (*.suf).....	44
Example	45
Appendix 4: Calibration Library File (*.cvi).....	46
Example	46
Appendix 5: Calibration Files (*.cal)	48
Example	48
Appendix 6: Parameter Value Files (*.pv).....	49
Example	50
Appendix 7: Theoretical Background for Estimating Hydraulic Properties of Test Intervals.....	53
Single-Hole Hydraulic Tests in Fractured Rock	53

Fluid-Injection Tests.....	55
Fluid-Withdrawal Tests.....	56
Steady-State Flow.....	57
Transient Flow - Confined Aquifer	58
Transient Flow - Semi-Confined Aquifer with Leakage	59
Transient Flow - Dual-Porosity Aquifer	60
Pressurized-Slug Tests.....	61
Hydraulic Tests with a Free-Water Surface	62
Fluid-Withdrawal Tests.....	62
Slug Tests.....	64

Figures

1. Initial appearance of the BAT ³ Analyzer.	5
2. Data Display window.	9
3. Data Conversion dialog box.....	16
4. New Calibration dialog box.....	20
5. Units Conversion Calculator.....	21
6. Field Calibration dialog box.....	23
7. Model Choices tab of the Model Parameters dialog box.....	27
8. Known Values tab of the Model Parameters dialog box.....	28
9. Model Parameters tab of the Model Parameters dialog box.....	29
10. Plot Controls tab of the Model Parameters dialog box.....	30
11. BAT3 window with Data Display, Downhole Transducers, and Flow Rate windows for example of estimating hydraulic properties from a fluid-injection test.....	34
12. Model Values chart showing results from a steady-state radial flow model and measured responses of the middle-zone transducer from a fluid-injection test.....	36

Tables

1. Units of display for flow meters, barometers, and pressure transducers.	17
2. Check measurements for pressure transducers during testing with the Multifunction BAT3.	24
3. Fluid injection tests recorded in the Raw Data file 01_339A.DAT.....	33

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
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:

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

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

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

BAT³ ANALYZER: REAL-TIME DATA DISPLAY AND INTERPRETATION SOFTWARE FOR THE MULTIFUNCTION BEDROCK-AQUIFER TRANSPORTABLE TESTING TOOL (BAT³)

By Richard B. Winston and Allen M. Shapiro

Abstract

The BAT³ Analyzer provides real-time display and interpretation of fluid pressure responses and flow rates measured during geochemical sampling, hydraulic testing, or tracer testing conducted with the Multifunction Bedrock-Aquifer Transportable Testing Tool (BAT³) (Shapiro, 2007). Real-time display of the data collected with the Multifunction BAT³ allows the user to ensure that the downhole apparatus is operating properly, and that test procedures can be modified to correct for unanticipated hydraulic responses during testing. The BAT³ Analyzer can apply calibrations to the pressure transducer and flow meter data to display physically meaningful values. Plots of the time-varying data can be formatted for a specified time interval, and either saved to files, or printed. Libraries of calibrations for the pressure transducers and flow meters can be created, updated and reloaded to facilitate the rapid set up of the software to display data collected during testing with the Multifunction BAT³. The BAT³ Analyzer also has the functionality to estimate calibrations for pressure transducers and flow meters using data collected with the Multifunction BAT³ in conjunction with corroborating check measurements. During testing with the Multifunction BAT³, and also after testing has been completed, hydraulic properties of the test interval can be estimated by comparing fluid pressure responses with model results; a variety of hydrogeologic conceptual models of the formation are available for interpreting fluid-withdrawal, fluid-injection, and slug tests.

Introduction

The Multifunction BAT³ is a borehole testing apparatus that can be used to collect groundwater samples for geochemical analyses and conduct various types of hydraulic and tracer tests in bedrock boreholes (Shapiro, 2007). The Multifunction BAT³ can be used to isolate discrete intervals of bedrock boreholes for testing, using two pneumatic borehole packers; the spacing between the two packers defines the test interval in the borehole. The borehole packers are inflated to form a hydraulic seal against the borehole wall, and equipment located between the packers is used to either inject or withdraw water in conducting hydraulic or tracer tests, or to collect water samples for geochemical analyses. A complete discussion of the downhole components of the Multifunction BAT³ and their operation is given in Shapiro (2007).

The Multifunction BAT³ is equipped with various sensors and data-acquisition equipment (Shapiro, 2007). The data-acquisition sensors include three flow meters to monitor the rates of fluid injection or withdrawal, three pressure transducers to monitor the fluid pressure in the test interval, as well as above and below the test interval in the borehole, and a pressure transducer to monitor barometric pressure. The Multifunction BAT³ uses a Campbell Scientific data logger to monitor and store the responses from the data-acquisition sensors, and the software that accompanies the Campbell Scientific equipment is used to access the data logger from a laptop computer and download the data from the data logger to the computer. The Campbell Scientific software can be configured to download the data from the data logger as it is collected during testing in the borehole, and save it to a file on a laptop computer.

In conducting hydraulic tests, tracer tests or geochemical sampling with the Multifunction BAT³, it is advantageous to monitor flow rates during hydraulic testing and the responses of pressure transducers as tests are being conducted. The software described in this report, referred to as the BAT³ Analyzer, is designed to display flow rates and fluid pressure responses as testing is conducted with the Multifunction BAT³. Visualizing the responses from the sensors in real time allows the user to ensure that the downhole apparatus is operating properly, and that test procedures can be modified to correct for unanticipated hydraulic responses arising from borehole conditions. The BAT³ Analyzer can also be used to interpret the hydraulic responses in the test interval and estimate hydraulic properties of the formation by comparing fluid pressure responses with model results; several hydrogeologic conceptual models can be used in interpreting the data, including, confined, leaky, and dual-porosity aquifers. This report describes the installation of the BAT³ Analyzer, its functionality, and its operation with the data-acquisition equipment of the Multifunction BAT³. This report assumes a basic knowledge of the skills needed to find and access files on a Windows operating systems, as well as the skills needed in operating a mouse for maneuvering in applications on a Windows operating system.

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 BAT³ Analyzer. For a first-time user of the BAT³ Analyzer, it is highly recommended that after reading this introductory material, the user should direct his attention to the summary of capabilities built into the BAT³ Analyzer that is given in the section “Overview of the BAT³ Analyzer” on page 3, the installation procedures given in the section “Installing and Starting the BAT³ Analyzer” on page 4, the procedures for opening and manipulating data files in the section “Opening and Saving Data Files” on page 8, and the section “Applying Calibrations to Raw Data” on page 15, which gives the procedures for converting the data collected from the sensors employed with the Multifunction BAT³ to physically meaningful units. These sections of the document will provide the user with the rudiments of operating the BAT³ Analyzer for the purpose of collecting and visualizing data during the operation of the Multifunction BAT³.

The remainder of the report gives details on formatting the data charts, printing and saving the data charts, procedures for interpreting the data to estimate hydraulic properties of the intervals tested, and time-saving operations that allow rapid setup of the BAT³ Analyzer prior to collecting data from the sensors attached to the Multifunction BAT³. As more familiarity is gained with the rudimentary operation of the BAT³ Analyzer, the user should consult the appropriate sections of this document listed in the Contents. Also, because this document is written as a reference manual, it contains some degree of redundancy, so that the document does not have to be read sequentially.

In addition, frequent references are made to sections and page numbers where related information can be found.

Overview of the BAT³ Analyzer

The sensors (pressure transducers and flow meters) used by the Multifunction BAT³ to monitor hydraulic responses during testing are wired to a Campbell Scientific data logger (Shapiro, 2007). The data logger monitors the responses of the sensors at a predetermined interval and stores the data internally. The data logger is connected to a laptop computer, and the software that accompanies the Campbell Scientific equipment downloads data from the data logger to a data file on a laptop computer. Connections between the laptop computer and the data logger, and the programs needed to operate the data logger for the sensors attached to the Multifunction BAT³ are discussed in Shapiro (2007).

To display and interpret data from the flow meters and pressure transducers during testing conducted with the Multifunction BAT³, the BAT³ Analyzer operates simultaneously with the Campbell Scientific software on the laptop computer that is connected to the Campbell Scientific data logger used by the Multifunction BAT³ for data acquisition. The BAT³ Analyzer reads data from a designated file on the laptop computer at a predetermined interval and displays the data. The BAT³ Analyzer expects a prescribed format for the data listed in the data file. Shapiro (2007) discusses the format of the data files collected by the Campbell Scientific software. An explanation of the data file created by the Campbell Scientific data logger used for data acquisition by the Multifunction BAT³ is also discussed in Appendix 1 of this report.

The BAT³ Analyzer also can be used to display and interpret data in files that have been collected previously. In this situation, the Campbell Scientific software does not need to be operating. The BAT³ Analyzer can read an existing data file, provided that it has the proper format.


The BAT³ Analyzer reads and performs operations on what is referred to as a **Raw Data** file. The “raw” data are the measured responses of the sensors (transducers and flow meters) as they are collected by the data-acquisition equipment of the Multifunction BAT³. For example, the responses from the pressure transducers, measured in millivolts (mv), and the frequency of the flow meters, measured in Hertz (Hz), are recorded and stored by the data logger, and downloaded automatically from the data logger to a data file on the laptop computer. Calibrations for these sensors relating the millivolt response to pressure, and the flow meter frequency to a flow rate are not programmed into the data-acquisition programs used by the Multifunction BAT³. Calibrations applied to the various sensors are regarded as interpretations applied to the “raw” data. The BAT³ Analyzer reads and performs operations on the “raw” data, but does not alter the “raw” data file. The BAT³ Analyzer can apply calibrations to the “raw” data to display the data in terms of physically meaningful values, and can save the interpreted data in a separate **Interpreted Data** file. During testing with the Multifunction BAT³, the data from the sensors can be displayed with the BAT³ Analyzer using assumed calibrations, or factory, laboratory, or field calibrations. If updated calibrations are provided at a later time, the “raw” data file can be revisited and the updated calibrations can be applied.

The BAT³ Analyzer is designed so that displays and interpretation of the data collected with the Multifunction BAT³ can be setup quickly and easily. The BAT³ Analyzer has the following functionality:

- The 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
- Calibrations for the sensors can be applied to the “raw” data to display sensor responses as physically meaningful values
- Data files with calibrations applied to the “raw” data can be saved for later use and interpretation
- Calibrations of pressure transducers and flow meters can be conducted from selected measurements in the **Raw Data** files
- Libraries of calibrations for sensors used by the Multifunction BAT³ can be created, saved, and updated, and then reloaded into the software
- Combinations of sensor calibrations frequently used to interpret pressure transducers and flow meter responses can be created, saved and reloaded
- Interpretations of transducer responses to pumping, fluid-injection and slug tests can be conducted using various hydrogeologic conceptual models of the formation to estimate hydraulic properties of the test interval
- Graphical displays of data and model results can be saved to files, or printed

Installing and Starting the BAT³ Analyzer

The BAT³ Analyzer is designed to operate on computers with the Windows 2000, or XP operating systems. The laptop computer used in conjunction with testing with the Multifunction BAT³ should have minimum system requirements of 1.7 megabytes free disk space, a monitor resolution of at least 1024 pixels by 768 pixels, and a mouse or other pointing device.

The BAT³ Analyzer consists of two files: **BAT3.exe** and **BATMODEL.dll**. To install the software, the user should run the installation program for the BAT³ Analyzer. The installation program will prompt the user for a disk storage location to place the files needed for executing the BAT³ Analyzer. The icon for the **BAT3.exe** file is . Double-clicking on **BAT3.exe** file, or the icon, starts the software. A shortcut to the software can be placed on the Desktop window, and in the Start Menu of the computer; the user is prompted during the installation to conduct these operations.

Other files installed with the BAT³ Analyzer include **BAT3.chm**, and **TeeUser7.chm**, which are help files that can be called from within the software. The file **BAT3_Lab.cvl** is a library of calibrations that are used to convert the sensor responses to physically meaningful values. The calibration library is a compilation of factory and laboratory calibrations for the pressure transducers, flow meters, and the barometric sensors that are used with the Multifunction BAT³. This calibration library is updated periodically to reflect updates in the calibrations. Also, files **01_339A.DAT** and **01_339_inj.suf** contain data and calibrations used in this report for the purpose of illustrating the operations of the BAT³ Analyzer.

Windows, Menus, and Icons

When the BAT³ Analyzer is started, the appearance will be similar to that shown in figure 1. The rectangular area used by the program is the “main” program “window,” or **BAT3** window. At startup, there are 5 smaller windows within the **BAT3** window. One of these windows is a table that displays the digital data (**Data Display**) from the sensors used by the Multifunction BAT³. The other four windows are sensor windows displaying charts of the data plotted as a function of time. The sensor windows include **Downhole Transducers**, **Flow Rate**, **Temperature**, and **Barometric Pressure**. The **Downhole Transducers** chart displays the responses of the three downhole pressure transducers. The **Flow Rate** chart displays the fluid-injection or fluid-withdrawal rate from flow meters attached to the Multifunction BAT³, and the **Temperature** and the **Barometric Pressure** charts display the panel temperature and the barometric pressure, respectively, from sensors located at the data-acquisition device used by the Multifunction BAT³. Moving the cursor over the **Data Display** window or one of the sensor windows, and clicking the left mouse button will make that window the active window in the **BAT3** window.

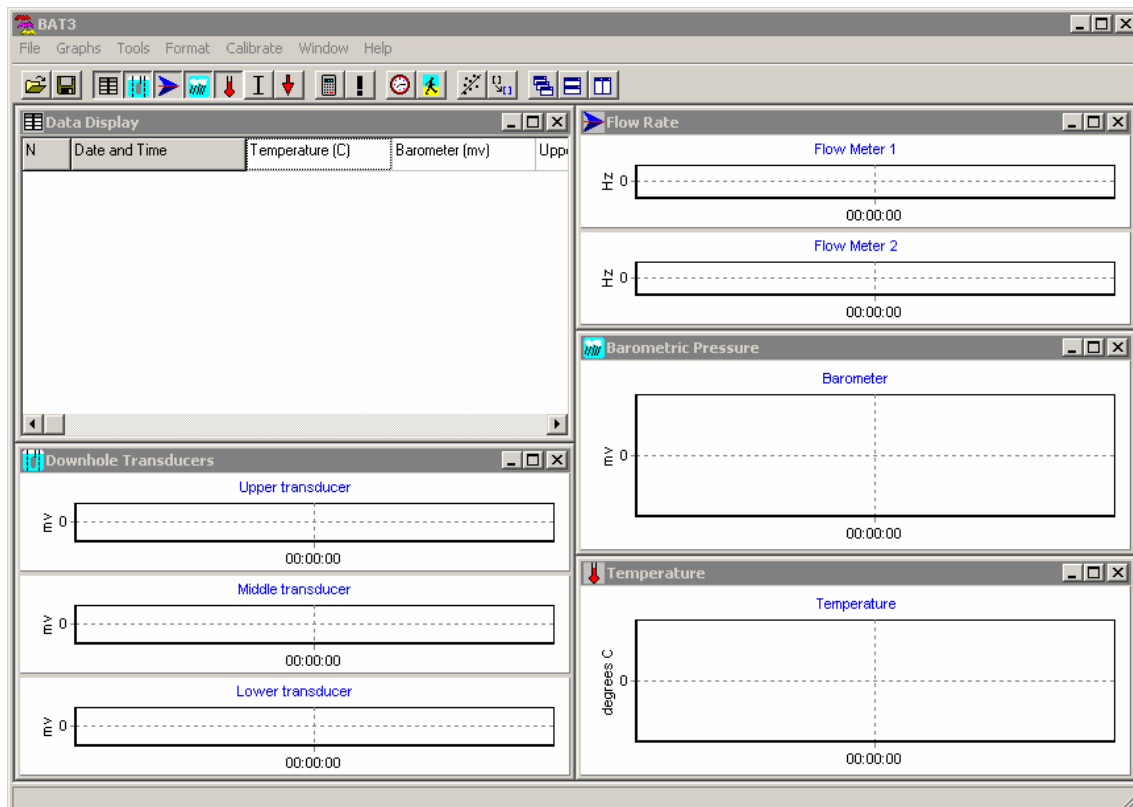




















Figure 1. Initial appearance of the BAT³ Analyzer.








The **BAT3** window and the 5 windows it contains can be resized by clicking and dragging the edges or corners of the window. A window can be minimized by clicking the minimize button  in the upper left corner of the window. A minimized window will be reduced to an icon and caption at the bottom of the main window or onto the Windows Taskbar together with “restore”, “maximize” and “close” buttons. Clicking the restore button  on a window that has been minimized or double-clicking on its caption restores it to its previous position. A window can be

maximized by clicking the maximize button  in the upper right corner of the window. A maximized window will fill the entire available area in the main window or on the Windows desktop. Clicking the close button  in the upper right corner of the window closes the window. Closing the **BAT3** window of the program causes the program to terminate. Closing one of the smaller windows causes it to disappear; however, it can be shown again by selecting the corresponding item under the **Graphs** menu.

Buttons on the toolbar also assist the placement of the open windows in the **BAT3** window. The buttons , , and  will respectively cascade, tile horizontally, or tile vertically the open windows to fill the space of the **BAT3** window. After clicking one of these buttons, further adjustments in the size of the windows can be obtained by clicking and dragging either the edges or corners of the windows.

A toolbar is available above the main program window. The toolbar has a series of buttons that represent frequently used menu items. Above the toolbar in the main program window are various menus. The menus and the items listed under each menu are listed below. In the list below, if a menu item has an image next to it, clicking the button on the toolbar with the same image has the same effect as selecting the menu item.

- File
 -  Open
 -  Save
 - Save As Image
 - Exit
- Graphs
 -  Data Display
 -  Transducer
 -  Flow Meter
 -  Barometer
 -  Temperature
 -  Use Previously Interpreted Data
 -  Go to Bottom
- Tools
 -  Units Conversion
 -  Model Parameters

- Format
 -  Starting Time / Update Interval
 -  Format Chart
- Calibrate
 -  Calibrate
 -  Choose Calibrations
- Window
 -  Cascade
 -  Tile Horizontally
 -  Tile Vertically
 - Minimize All
 - Restore All
 - Data Display
 - Downhole Transducers
 - Flow Rate
 - Barometric Pressure
 - Temperature
- Help
 - Contents
 - About

If the Flow Rate chart is the active window, an additional menu will be displayed with the following title and menu items:

- Charts
 - Show Two Flow Meters

If the **Barometric Pressure** chart is the active window and a data file has been opened, an additional menu will be accessible with the following title and menu items:

- Time for Barometer Chart
 - Set Starting and Ending Times
 - Use Same Times as Other Charts

If the **Temperature** chart is the active window and a data file has been opened, an additional menu will be accessible with the following title and menu items:


- Time for Temperature Chart
 - Set Starting and Ending Times
 - Use Same Times as Other Charts


For the remainder of this document, parts of the discussion of the BAT³ Analyzer will be printed in **bold** type. When describing menu items, a vertical line is used to separate menu items from submenu items. For example, choosing the **Open** submenu item from the **File** menu item would be printed as **File|Open**. In addition, the names of windows, buttons, and dialog boxes that appear in the BAT³ Analyzers will also be denoted by **bold** type.

Opening and Saving Data Files


The BAT³ Analyzer is designed to monitor and interpret data from sensors used during testing in boreholes with the Multifunction BAT³ (Shapiro, 2007). If display and interpretation is to be conducted during testing with the Multifunction BAT³, then the data file created by the Campbell Scientific software and downloaded to the laptop computer must be opened by the BAT³ Analyzer. The data file created by the Campbell Scientific software has a file extension of “dat”, for example, 01_339A.DAT. Files with the extension “dat” are **Raw Data** files; the structure of data in the “dat” files is given in Appendix 1.

The BAT³ Analyzer also can open files previously operated on by the BAT³ Analyzer, where calibrations have been applied to the “raw” data collected from the Multifunction BAT³. These data files, referred to as **Interpreted Data** files have the file extension “idf”, for example, 01_339A.idf. The “idf” files contain the “raw” data, the calibrations applied to the “raw” data, the interpreted data, and the physical units associated with the interpreted data. The structure of the “idf” files is given in Appendix 2.



To open a data file, select **File|Open** or click the **Open File** button . If a data file is already open, the user will be asked whether to save the existing data in the BAT³ Analyzer as an **Interpreted Data** file. Next the user must select the data file from the dialog box; the user may have to browse the disk space of the computer for the location of the appropriate data file. After clicking **Open** on the dialog box, the user will be asked whether or not to reset all “conversions” to their default values; “conversions” are the application of calibrations for the various sensors that convert the “raw” data to physically meaningful values. A complete discussion of converting “raw” data to physically meaningful values is presented in the section “Applying Calibrations to Raw Data” on page 15. The data in the file that has been opened is then displayed in the five windows: **Data Display, Downhole Transducers, Flow Rate, Barometric Pressure and Temperature**.

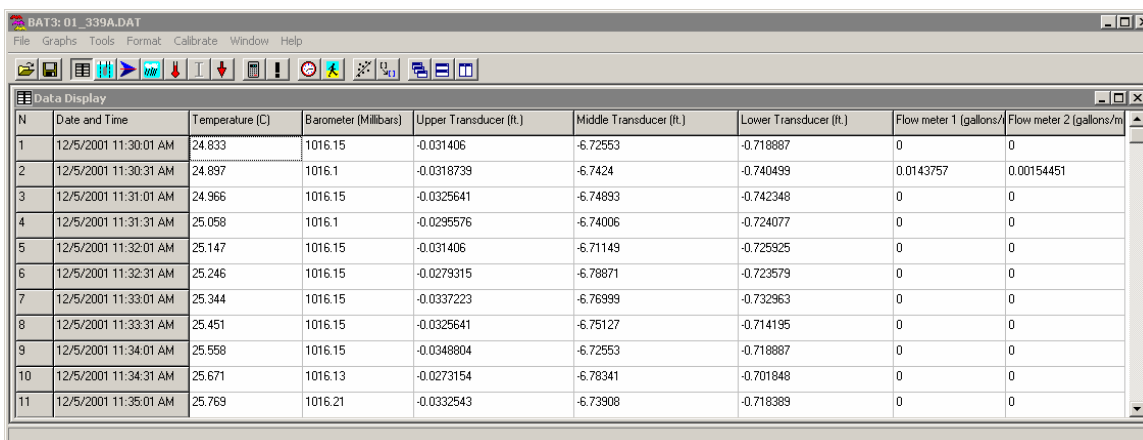
If an “idf” file is opened, the user can choose to use the sensor calibrations originally applied to the data, or apply different sensor calibrations to the raw data. This choice can also be made from the **Graphs** menu or by clicking on the **Interpreted data** button .

After viewing and operating on either a “dat” or “idf” file, the user can save the data as an “idf” file, which will contain the original data plus information on how the data were converted from the “raw” data to physically meaningful values. To save the data as an “idf” file, choose

File|Save or click the **Save** button  to save the data. The user must specify the name and disk location of the file to be saved.



Data Display Window

The **Data Display** window (fig. 2) contains a table of all the data from the file opened by the BAT³ Analyzer. Not all of the data, however, needs to be displayed in the sensor windows containing the charts of the time-varying sensor responses. The data displayed in the sensor charts is adjusted by using the **Format|Format Chart** menu item or the **Format Chart** button . (see section “Formatting the Time Axis on Charts” on page 13 and “Formatting Other Chart Attributes” on page 14). The user can choose not to display the **Data Display** window in the **BAT3** window by selecting the **Graphs|Data display** menu item or clicking on the **Data Display** button  on the toolbar.




N	Date and Time	Temperature (C)	Barometer (Millibars)	Upper Transducer (ft.)	Middle Transducer (ft.)	Lower Transducer (ft.)	Flow meter 1 (gallons/m)	Flow meter 2 (gallons/m)
1	12/5/2001 11:30:01 AM	24.833	1016.15	-0.031406	-6.72553	-0.718887	0	0
2	12/5/2001 11:30:31 AM	24.897	1016.1	-0.0318739	-6.7424	-0.740499	0.0143757	0.00154451
3	12/5/2001 11:31:01 AM	24.966	1016.15	-0.0325641	-6.74893	-0.742348	0	0
4	12/5/2001 11:31:31 AM	25.058	1016.1	-0.0295576	-6.74006	-0.724077	0	0
5	12/5/2001 11:32:01 AM	25.147	1016.15	-0.031406	-6.71149	-0.725925	0	0
6	12/5/2001 11:32:31 AM	25.246	1016.15	-0.0279315	-6.78871	-0.723579	0	0
7	12/5/2001 11:33:01 AM	25.344	1016.15	-0.0337223	-6.76999	-0.732963	0	0
8	12/5/2001 11:33:31 AM	25.451	1016.15	-0.0325641	-6.75127	-0.714195	0	0
9	12/5/2001 11:34:01 AM	25.558	1016.15	-0.0348804	-6.72553	-0.718887	0	0
10	12/5/2001 11:34:31 AM	25.671	1016.13	-0.0273154	-6.78341	-0.701848	0	0
11	12/5/2001 11:35:01 AM	25.769	1016.21	-0.0332543	-6.73908	-0.718389	0	0

Figure 2. Data Display window.

The **Data Display** window can also be minimized by using the minimization button  at the upper right of the **Data Display** window. With this operation, the **Data Display** window is minimized, and the title bar of the window appears in the lower corner of the **BAT3** window of the application. The maximization button  on the upper right of the **Data Display** window enlarges the **Data Display** window so that it fills the entire **BAT3** window of the application; with this operation, the sensor windows are covered by the **Data Display** window.


The size of the **Data Display** window can also be adjusted in the **BAT3** window of the BAT³ Analyzer. Moving the cursor to a corner or edge of the **Data Display** window, and depressing the left mouse button and dragging, resizes the **Data Display** window. The vertical and horizontal scroll bars on the **Data Display** window can be used to view the table of data values. Scrolling to data in the table associated with a specific date and time can also be conducted by first moving the cursor over a window associated with a particular sensor and clicking the left mouse button to make it the active window. Moving the cursor directly over the data curve at the desired time and then clicking the left mouse button changes the **Data Display** window so that the corresponding data are visible in the **Data Display** window.

The number of rows in the table in the **Data Display** window is equal to the number of data points in the file opened by the BAT³ Analyzer. If testing with the Multifunction BAT³ is being conducted, and the BAT³ Analyzer is set to update the **Data Display** and sensor windows as the data is recorded, the number of rows in the **Data Display** window will increase. Using the mouse to depress the **Down-Arrow** button  will force the **Data Display** window to scroll down to the bottom of the table as data are collected, so that the most recently collected data are visible on the last row of the table. The same operation can be conducted by using the **Graphs|Go to bottom** menu item.

The table in the **Data Display** window has 9 columns. The first column is a counter, the second column gives the date and time associated with the sensor values listed in the remaining columns. Column 3 is the panel temperature (in degree Celsius) of the Campbell Scientific data logger used by the Multifunction BAT³ for data acquisition. Columns 4 through 9 give the responses of the barometric pressure sensor, the three downhole pressure transducers, and the two flow meters. The units associated with the sensor responses will depend on whether calibrations have been applied to the various sensors. A discussion of applying calibrations to the various sensors is given in the section “Applying Calibrations to Raw Data” on page 15.

The values in the cells of the table in the **Data Display** window cannot be edited, but the contents of an individual cell in the table can be copied and then pasted into other applications or into a location in the BAT³ Analyzer that accepts numerical input. For example, the **Model Parameters** dialog box requires the entry of various physical quantities to estimate the hydraulic properties of the interval being tested with the Multifunction BAT³, and some of those physical quantities need to be taken from the **Data Display** window; a further discussion of the estimation of hydraulic properties of the test interval using the **Model Parameters** dialog box is given in the section “Estimating Hydraulic Properties of a Test Interval” on page 25. The contents of a particular cell in the table of the **Data Display** window is copied by first moving the cursor over the **Data Display** window and clicking the left mouse button to make it the active window. The particular cell in the table is then found by using the scroll bars, and the cursor is moved over the contents of the cell in the table. Clicking the left mouse button once makes the cell the active cell, and clicking the left mouse button again highlights the contents of the cell. Using **control-c** copies the contents of the cell to the system clipboard; **control-v** pastes the contents of the cell to an appropriate location either in the BAT³ Analyzer or another application.

Updating Data During Testing


The BAT³ Analyzer can operate simultaneously with the data acquisition equipment of the Multifunction BAT³, so that as data are collected (and stored on the laptop computer), the BAT³ Analyzer reads the newly acquired data and updates the table in the **Data Display** window and the charts of the sensor responses. The frequency with which the BAT³ Analyzer checks for newly acquired data is specified using the **Format|Starting Time / Update Interval** menu item or clicking on the **Starting Time / Update Interval** button . In the dialog box, the user enters the update frequency (in seconds), or uses the arrow keys to change the update frequency.



The update frequency specified in the BAT³ Analyzer does not affect the frequency with which data are collected using the data-acquisition equipment of the Multifunction BAT³. The method of changing the frequency of data acquisition of the Multifunction BAT³ is discussed in

Shapiro (2007). In many applications of the Multifunction BAT³, measurements from the sensors are collected once every 30 seconds. The time interval for the update frequency specified in the BAT³ Analyzer should be smaller than the time interval associated with the data acquisition from the Multifunction BAT³ to ensure that data are recognized by the BAT³ Analyzer soon after they are collected and downloaded to the laptop computer. The default value for the update frequency in the BAT³ Analyzer is 5 seconds.

Sensor Windows

The BAT³ Analyzer graphically displays the data from the sensors attached to the Multifunction BAT³ in sensor windows within the **BAT3** window. Upon starting the BAT³ Analyzer, sensor windows are displayed for **Temperature**, **Barometric Pressure**, **Downhole Transducers**, and **Flow Rate**. The user can choose not to display a particular sensor window in the **BAT3** window by selecting **Transducer**, **Flow Meter**, **Barometer** or **Temperature**, from the **Graphs** menu item, or clicking on the button on the tool bar that corresponds to a particular sensor.

The buttons on the tool bar have the following appearance , and from left to right they correspond to the **Downhole Transducers**, **Flow Rate**, **Barometric Pressure** and **Temperature** windows. Selecting the menu item or the button for a particular sensor window acts to toggle the visibility of the associated sensor window.

Moving the cursor over a particular sensor window and clicking the left mouse button makes that window the active window in the application. The size of the active sensor windows can be changed by moving the cursor to the corner or edge of window and clicking and dragging with the left mouse button to alter the dimensions of the window. The charts in the sensor window are resized as the sensor window is resized. Sensor windows can also be minimized by using the minimization button  at the upper right of the window. With this operation, the sensor window is minimized, and the title bar of the window appears in the lower corner of the **BAT3** window of the application. The maximization button  on the upper right of the sensor window enlarges the sensor window so that it fills the entire **BAT3** window of the application; with this operation, the maximized sensor window covers the **Data Display** window and the other sensor windows visible in the application.

Temperature

The **Temperature** window displays a chart of the panel temperature on the Campbell Scientific data logger in degrees Celsius as a function of time. Because the panel temperature may not change as frequently as the other sensors attached to the Multifunction BAT³ during downhole testing, the time axis of this sensor window can be set independently of the other sensor windows. Moving the cursor over the **Temperature** window and clicking the left mouse button makes this window the active window. With the **Temperature** window as the active window, selecting the menu item **Time for Temperature Chart|Set Starting and Ending Times** allows the user to specify the limits of the time axis independently of the other sensor windows. Choosing this option displays a dialog box for selecting the limits of the time axis. The choices in the dialog box are discussed in the section “Formatting the Time Axis on Charts” on page 13. Alternatively, the user can select the menu item **Time for Temperature Chart|Use Same Times as Other Charts** with the **Temperature** window as the active window. This option makes the time axis on the chart of the temperature versus time the same as the time axes of the other charts on the other sensor windows.

Barometric Pressure

The **Barometric Pressure** window displays the response of the barometric pressure sensor mounted on the data-acquisition panel of the Multifunction BAT³. The time axis of this sensor window can be set independently of other sensor windows in the same way as the **Temperature** window. The barometric sensor used in the Multifunction BAT³ is described in Shapiro (2007). The “raw” data from the barometric sensor is given in millivolts. Upon opening the BAT³ Analyzer, no calibrations are applied to the raw data from the various sensors. Thus, the response of the barometric sensor by default is displayed in millivolts. A calibration that converts the millivolt response of the barometric sensor to physically meaningful values can be applied so that the chart on the **Barometric Pressure** window displays physically meaningful units. The section “Applying Calibrations to Raw Data” on page 15 discusses the application of calibrations for the various sensors to convert raw data to physically meaningful units.

Downhole Transducers

The **Downhole Transducers** window displays charts of the upper, middle and lower transducers used in the Multifunction BAT³. The pressure transducers used in the Multifunction BAT³ are discussed in Shapiro (2007). The middle transducer corresponds to the test interval between the two inflatable packers in the Multifunction BAT³. The upper transducer corresponds to the fluid pressure measured above the top packer in the downhole apparatus, and the lower transducer corresponds to the fluid pressure measured below the bottom packer in the downhole apparatus. The raw data from the transducers are given in millivolts. Upon opening the BAT³ Analyzer, no calibrations are applied to the raw data from the various sensors. Thus, the response of the transducers by default is displayed in millivolts. A calibration that converts the millivolt response of the transducers to physically meaningful values can be applied so that the chart on the **Downhole Transducers** window displays physically meaningful units. The section “Applying Calibrations to Raw Data” on page 15 discusses the application of calibrations for the various sensors to convert raw data to physically meaningful units.


Flow Rate

The **Flow Rate** window displays the response of the flow meters used by the Multifunction BAT³ to measure the rate at which fluid is injected into the test interval or the rate at which fluid is pumped from the test interval. For fluid injection tests conducted with the Multifunction BAT³, two flow meters are available to measure a wide range of fluid injection rates; see Shapiro (2007) for the specifications of the flow meters used for fluid-injection testing. Therefore, for fluid-injection testing with the Multifunction BAT³, it is useful to display charts of the responses of both flow meters on the **Flow Rate** window. For fluid-withdrawal testing, only a single flow meter is used to monitor the pumping rate. With the menu item **Chart|Show Two Flow Meters** checked, charts for two flow meters are displayed on the **Flow Rate** window. If this menu item is not checked, then only one flow meter is displayed. Selecting the menu item **Chart|Show Two Flow Meters** acts to switch between one and two flow meter charts appearing on the **Flow Rate** window. If the responses of only one flow meter are displayed, the first flow meter in the data string is assumed to be the operational flow meter (see Appendix 1 for the structure of the **Raw Data** file).

The raw data from the flow meters used with the Multifunction BAT³ are given as a frequency measured in Hertz (Hz). Upon opening the BAT³ Analyzer, no calibrations are applied to the raw data from the various sensors. Thus, the responses of the flow meters by default are

displayed in Hz. A calibration that converts the Hz to physically meaningful values can be applied so that the chart on the **Flow Rate** window displays physically meaningful units. The section “Applying Calibrations to Raw Data” on page 15 discusses the application of calibrations for the various sensors to convert raw data to physically meaningful units.

Formatting the Time Axis on Charts

The time axis of the sensor windows can be adjusted so that only portions of the data are displayed, rather than the entire data in the data file opened by the BAT³ Analyzer. Formatting the time axis is conducted by selecting **Format|Starting Time / Update Interval** menu item or clicking on the **Starting Time / Update Interval** button . This operation opens a dialog box, where the user specifies the starting and ending times for the time axis on the sensor windows in one of three ways.

1. **Use first time in data set:** The data in the sensor windows are plotted starting with the first time in the data file. The user can specify the number of minutes to plot after the first time in the data file by entering a value in the Number of minutes to plot box, or using the arrow buttons to increase or decrease the value appearing in this box. Entering zero in the Number of minutes to plot box will result in all of the data being plotted.
2. **Specify duration only:** For this option, the user specifies the data to be plotted in the time interval (given in minutes) prior to the time of the last data read in the file. This option is useful for monitoring the results of tests as they are being conducted. As data are being downloaded from the data logger to the laptop computer, the BAT³ Analyzer reads the Raw Data file and updates the sensor windows to include only the last data collected in the time interval specified by the user.
3. **Specify starting time and duration:** For this option, the user specifies both the starting time for the display and the duration, in minutes, to be plotted. This option is useful for visualizing the data for a specific time interval, for example, examining the data for a specific test or time interval after testing has been completed.


The time axes for the sensors displayed on the **Temperature** and **Barometric Pressure** windows can be set independently using the **Time for Temperature Chart** menu item when the **Temperature** window is the active window, or the **Time for Barometer Chart** menu item when the **Barometric Pressure** window is the active window. If the **Set Starting and End Times** menu item is checked under this menu items, the time axis will not be updated when the charts on the **Downhole Transducers** and **Flow Rate** windows are updated using the **Format|Starting Time / Update Interval** menu item. If the **Use Same Time as Other Charts** menu item is checked for the **Temperature** and/or **Barometric Pressure** windows, updating the charts using the **Format|Starting Time / Update Interval** menu item will result in the time axes of the charts for the temperature and/or barometric pressure being updated as well.

Zooming and Panning Charts



Data displayed in the charts of the sensor windows also can be changed by “zooming” and “panning” the charts. To zoom into a portion of the data on a specific chart, the chart is selected by moving the cursor over the chart of interest and clicking with the left mouse button, to make it the

active chart. Zooming into a portion of the chart is conducted by depressing the left mouse button and dragging the cursor diagonally to define the limits associated with a rectangular box. After releasing the left mouse button, this action zooms in on the portion of the chart in the box that was outlined with the cursor. Both the horizontal (time) and the vertical axes are rescaled for the selected chart. The axes of the other charts are unaffected by this action.

Panning is conducting by clicking on the chart of interest, to make it the active chart, and then depressing the right mouse button and moving the cursor on the chart to translate the data along the horizontal (time) and vertical axes. This operation does not change the scale associated with the horizontal (time) and vertical axes, and it only affects the chart of interest. Further information on zooming and panning charts can be found in the **Help** files.

After zooming or panning a particular chart, the chart can be reformatted so that the time axis conforms with the time axes of the other charts by using the **Format|Starting Time / Update Interval** menu item or clicking on the **Starting Time / Update Interval** button . The time axes on all the charts in the sensor windows can be specified using the options discussed in the section “Formatting the Time Axis on Charts” on page 13.

Formatting Other Chart Attributes

The BAT³ Analyzer allows the user to format almost all the attributes of the charts on the sensor windows. To format the chart attributes, the user selects the **Format|Format Chart** menu item or the **Format Chart** button , and then selects the chart of interest in the dialog box. This operation brings up a dialog box with **Chart** and **Series** tabs for the sensor of interest. Controls on the **Series** tab allows the user to change the appearance of the data on the chart, for example, the color and thickness of the line representing the data, the appearance of data points and other features. Controls on the **Chart** tab allow the user to change the appearance of the axes, the background color of the chart, the maximum and minimum limits for each axis and other features. Additional information on the formatting of charts can be obtained by clicking the **Help** button on the dialog box used to format the chart. The user may also click on the **Help Question Mark**  on the upper right corner of the dialog box. Moving the **Help Question Mark** to a control on the dialog box and then clicking on the item shows the help window associated with that item.

Saving and Printing Chart Images

Images of the charts in the sensor windows can be saved to a file or printed from the BAT³ Analyzer. The menu command **File|Save as image** opens a dialog box for the user to select a chart appearing in one of the sensor windows. The user is then prompted to name the image file and select its storage location. The user must also choose the format for the image file. The default format is the “Enhanced Windows Metafile” with the file extension “emf”; however, the user may also specify another format for the image file, either a Windows Metafile with file extension “wmf”, or a bitmap file, with the file extension “bmp”.


Images of a chart can also be exported to a file by using the menu item **Format|Format Chart** and specifying a particular data chart in the **Format Charts** dialog box. Clicking on the **Chart|General** tab for the chart under consideration, and then clicking on the **Export** button will result in a dialog box appearing where a file type needs to be specified. The user can then choose to

copy the chart to the system clipboard or save the chart to a file using the appropriate buttons on the **Export TeeChart** dialog box. If the chart is to be saved to a file, the user will then be prompted to name the file and select its storage location.

Charts appearing in a sensor window can also be sent to a printer from within the BAT³ Analyzer. After selecting the menu item **Format|Format Chart** and specifying a particular data chart, the user should select the **Chart|General** tab of the dialog box, and then click the **Print Preview** button. Another dialog box appears with a preview of the chart to be printed. Modifications in the print appearance can be made using the controls in this dialog box, and the chart can be sent to a printer by clicking the **Print** button.

Applying Calibrations to Raw Data

The BAT³ Analyzer reads a data file that is collected and downloaded to a laptop computer by the data-acquisition equipment of the Multifunction BAT³. The responses of the barometer and transducers attached to the data-acquisition equipment of the Multifunction BAT³ are measured and recorded in millivolts, and the responses of the flow meters are measured and recorded in Hz. Factory, laboratory, or field calibrations are required to convert these responses to physically meaningful values. By default the BAT³ Analyzer does not apply conversions to the “raw” data read from the data file, and by default the charts of data on the sensor windows are given in the units of the “raw” data. The BAT³ Analyzer, however, can apply calibrations to the “raw” data and display a table of the digital information and charts in the sensor windows in physically meaningful units. The application of calibrations to the “raw” data, however, does not alter the data file that is read by the BAT³ Analyzer. Thus, if the calibrations that are applied to the data need to be modified, the original data collected by the data-acquisition equipment of the Multifunction BAT³ can still be accessed.

To apply calibrations to the “raw” data read by the BAT³ Analyzer and to choose the units in which the data should be displayed, the user must select the **Calibrate|Choose Calibrations** menu item or click the **Choose Calibration** button . Performing this operation opens the **Data Conversion** dialog box (fig. 3). In the **Data Conversion** dialog box, the user can enter numerical values that change the “raw” data to physically meaningful units, as well as specify the units that should be displayed on the charts in the sensor windows. There are two sections on the **Data Conversion** dialog box; the top section of the dialog box contains tabs that refer to the various sensors used by the Multifunction BAT³. The bottom section of the dialog box contains pull down menus for choosing the units of display for the barometer, flow meters and transducers. The bottom section of the **Data Conversion** dialog box also contains buttons for (1) creating, storing, reloading, and editing sensor calibrations, and (2) saving and reloading sets of calibrations used by Multifunction BAT³. The later two functions of the **Data Conversion** dialog box are discussed in the sections “Saving and Loading a Conversion Setup File” on page 18, and “Creating, Saving, and Loading a Calibration Library” on page 18.

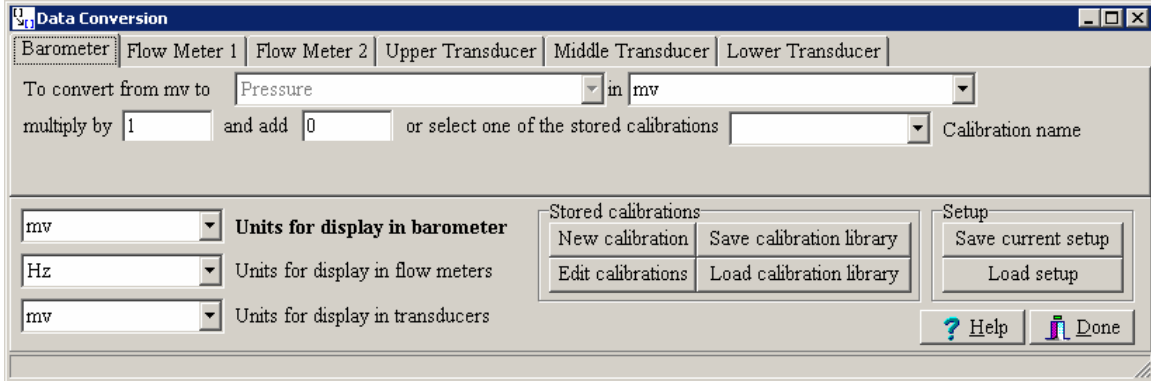


Figure 3. Data Conversion dialog box.

The calibrations for the various sensors that are used by the Multifunction BAT³ have linear relations between their measured quantities (for example, mv or Hz) and their associated physically meaningful units. The calibration is generally written as

$$Y = A X + B$$

where X is the measured quantity in mv for the barometer and the pressure transducers, and Hz for the flow meters, A and B are the multiplier and offset, respectively, that converts the measured value to physically meaningful units given by Y. The units of B are the same as the units of Y, and the units of A are the units of Y divided by the units of the measured quantity (mv or Hz).

In the **Data Conversion** dialog box, **the user must first choose the units for display of the barometer, flow meters, and pressure transducers in the bottom part of the Data Conversion dialog box.** These are the units that will be displayed on the charts of the sensor windows. Table 1 gives a list of the units that can be used in displaying barometric pressure, the flow rate measured through the flow meters, and the pressure transducers. The units for display do not have to be the same as the units in which the calibration is defined. For example, the calibration for the barometer may use values of A and B that convert mv to barometric pressure in millibars; however the units of display on the sensor window for barometric pressure may be given in atmospheres, inches of mercury, or other units (see table 1). The BAT³ Analyzer automatically converts from the units associated with the calibration to the units of display for the sensor window.

Moving the cursor to the tab for a sensor on the top of the **Data Conversion** dialog box and clicking with the left mouse button will show the current conversion information for that sensor. To convert the “raw” data to physically meaningful values for display on the **Data Display** window and the sensor windows, the user must specify the multiplier and offset in the appropriate boxes for each of the sensors, as well as specifying the units associated with the conversion. The default values for the multiplier and offset are set to one (1) and zero (0), respectively. The multiplier, offset, and units of the calibration can be entered manually, or they can be loaded from a **Calibration Library** file, or from a previously stored **Setup** file of conversions for the sensors. Additional details about using conversion **Setup** files and calibration libraries are given in the sections “Saving and Loading a Conversion Setup File” on page 18, and “Creating, Saving, and Loading a Calibration Library” on page 18.

Table 1. Units of display for flow meters, barometers, and pressure transducers.

Flow Meters	Barometers	Pressure Transducers
Hz	mv	mv
m ³ /s	Pascals	cm
m ³ /min	Kilopascals	m
m ³ /hr	atmospheres	km
ft. ³ /s	Bars	in
ft ³ /min	Millibars	ft
ft ³ /hr	cm of Mercury	mi
gallons/s	Inches of Mercury	
gallons /min	Pounds per square inch	
gallons /hr	m of water (15 degrees C)	
	feet of water (15 degrees C)	

The multiplier and offset for the sensors that accompany the Multifunction BAT³ are given in Shapiro (2007). The calibrations given in Shapiro (2007) are from factory or laboratory calibration. Updates to these calibrations will be given in the calibration library file **BAT3_Lab.cvl** that is distributed with the BAT³ Analyzer. The user can also enter calibrations conducted under field conditions, and update the calibration library with such calibrations. The section “Calibrating Sensors” on page 21 describes the application of the BAT³ Analyzer in performing the field calibration of sensors, and the section “Creating, Saving, and Loading a Calibration Library” on page 18 provides information on creating and saving new calibrations for later use in the BAT³ Analyzer.

The units of display in the sensor window for the three pressure transducers used by the Multifunction BAT³ are units of length (see table 1). After choosing the desired units of length, the user must then choose for each transducer the reference datum associated with the transducer calibration, and the units associated with the calibration, which is also given in units of length; the units of length for the display on the sensor window does not have to be the same as the units of length associated with the calibration. The three choices for the reference datum associated with the transducer calibration are (1) depth to water below a given datum, (2) height of water above the transducer, and (3) elevation above a given datum. The user must enter values for the multiplier and offset that correspond with the reference datum in the appropriate boxes for each transducer.

The transducers that are supplied with the Multifunction BAT³ have been calibrated under laboratory conditions. The multiplier and offset for each transducer is defined with the reference datum being the height of water above the transducer sensor. The user can alter the offset of the transducer calibrations to define them with respect to another datum. These calibrations are discussed in Shapiro (2007) and a **Calibration Library** file, **BAT3_Lab.cvl**, giving these calibrations has been prepared for use with the BAT³ Analyzer.

The transducers that are used with the Multifunction BAT³ are absolute pressure transducers, which implies that when these transducers are removed from water they measure atmospheric pressure. Consequently, to obtain the fluid pressure when the transducer is placed in water, the barometric pressure must be subtracted from the measured pressure response. Associated with each transducer calibration in the **Data Conversion** dialog box is a checkbox that needs to be checked to correct the transducer response for barometric pressure. The BAT³ Analyzer uses the

measured barometric pressure to correct the measured transducer response to obtain the fluid pressure.


In defining the calibrations and entering the multiplier and offset for each sensor, the user needs to ensure that the calibration that is used corresponds to the sensor that is actually connected to the data-acquisition equipment of the Multifunction BAT³. There are multiple transducers and multiple flow meters that can be supplied with the Multifunction BAT³, depending on the application. The serial number associated with a given sensor should be checked against the serial number defined in the **Calibration Library** file.

Field calibrations of the various sensors used by the Multifunction BAT³ can also be conducted by the user, and this information can be entered by the user into the appropriate boxes in the **Data Conversion** dialog box, as well as creating or updating the **Calibration Library** file. The section “Calibrating Sensors” on page 21 discusses the capabilities of the BAT³ Analyzer in performing sensor calibrations. Shapiro (2007) also discusses the field calibration of transducers and flow meters. The section “Creating, Saving, and Loading a Calibration Library” on page 18 discusses how **Calibration Library** files can be updated and saved for future use.

Saving and Loading a Conversion Setup File

The same sensors are frequently used from day to day when testing with the Multifunction BAT³. Therefore, the same calibrations (multipliers and offsets) for the various sensors in the **Data Conversion** dialog box will need to be entered in setting up the BAT³ Analyzer to display data as it is being collected. To facilitate the rapid setup of the BAT³ Analyzer to display data during testing with the Multifunction BAT³, the BAT³ Analyzer can save the setup of the **Data Conversion** dialog box as a **Setup** file, so that it can be reloaded at another time. The **Setup** file contains the multipliers and offsets for the various sensors, the controls for correcting the pressure transducers for barometric pressure, and the units in which the various sensors are displayed on the sensor windows. The description and an example of a **Setup** file are given in Appendix 3.

To save the configuration of the **Data Conversion** dialog box, the user must move the cursor to the button **Save current setup** on the bottom of the **Data Conversion** dialog box and click with the left mouse button. This will prompt the user to enter the name and file location of the **Setup** file to be saved. The **Setup** file name will have the extension “suf”.

To load an existing **Setup** file, the user must enter the **Data Conversion** dialog box by selecting the **Calibrate|Choose Calibrations** menu item or clicking on the **Choose Calibration** button . Clicking with the left mouse button on the **Load setup** button on the bottom of the **Data Conversion** dialog box will prompt the user to choose the location and filename of an existing **Setup** file. Performing this operation configures the **Data Conversion** dialog box with the information in the **Setup** file.

Creating, Saving, and Loading a Calibration Library

There are multiple transducers, barometers, and flow meters that can be used with the Multifunction BAT³. Depending on the application, transducers and flow meters can be removed and replaced with other transducers and flow meters. The BAT³ Analyzer has the capability of

creating, saving, and loading a **Calibration Library** file that contains the calibration information for sensors that are used with the Multifunction BAT³. The format of the **Calibration Library** file is described in Appendix 4. The calibrations for the various sensors listed in the **Calibration Library** file can also be updated, if the calibration is known to change. The BAT³ Analyzer allows the user to load the calibration library and then select the calibrations that correspond to the sensors attached to the data-acquisition equipment of the Multifunction BAT³, or to edit the calibration associated with a particular sensor, if the calibration for that sensor is to be replaced or updated.

Calibrations can be created in either the **Data Conversion** dialog box, or using the calibration capability of the BAT³ Analyzer. The calibration capability of the BAT³ Analyzer is discussed in the section “Calibrating Sensors” on page 21. To create a new calibration for a sensor in the **Data Conversion** dialog box, the user clicks on the **New calibration** button on the bottom of the **Data Conversion** dialog box. This opens a **New Calibration** dialog box (fig. 4), where the user must choose the type of sensor, the units associated with the conversion, and the multiplier and offset for the calibration. In addition, the user must specify a calibration name. This name should be unique to a particular sensor. For example, there are several transducers that have a range of 100 pounds per square inch (psi) that can be used with the Multifunction BAT³. To distinguish the calibrations for each of these transducers, the range of the transducer and the serial number of the transducer are used in the calibration name. There is also space provided on the **New Calibration** dialog box to enter a short description of the calibration and the sensor, for example, the date of the calibration, and other distinguishing information about the sensor. After this information is entered, clicking the **OK** button temporarily stores the new conversion in active memory of the software application, and the user is returned to the **Data Conversion** dialog box. To permanently save the new calibration to a file, which would be available for use in the BAT³ Analyzer at a later time, the user must click on the **Save calibration library** button. This action prompts the user to define a file location and a file name for the **Calibration Library** file, with the file extension “cvi”.

An existing **Calibration Library** file can be loaded in the active memory of the BAT³ Analyzer to facilitate setting up the **Data Conversion** dialog box. To load a **Calibration Library** file, the user must open the **Data Conversion** dialog box and click on the **Load Calibration Library** button. The user is then prompted to open a **Calibration Library** file. **Prior to choosing calibrations from the Calibration Library file, the user must first define the display units on the bottom of the Data Conversion dialog box for the various sensors in units other than those associated with the raw data.** The user then selects a calibration name from the pull-down menu associated with each sensor. Choosing a specific calibration from the pull-down menu will automatically place the attributes of that conversion into the appropriate boxes in the **Data Conversion** dialog box.

Calibration Library files that have been loaded into the active memory of the BAT³ Analyzer can also be updated. Updating could involve adding a new calibration or editing an existing calibration. Adding a new calibration is discussed in the paragraphs above. Editing an existing calibration for a particular sensor is conducted by clicking on the **Edit calibrations** button on the bottom of the **Data Conversion** dialog box, which opens the **New Calibration** dialog box. From the pull-down menu of calibration names, the user chooses the calibration name. The information about the calibration name is then shown in the **New Calibration** dialog box, including the sensor type, the units of the calibration, the multiplier, and offset, and the description of the calibration. After modifying any of these parameters, clicking the **OK** button returns the user to the

Data Conversion dialog box. The user can also save the updates to a newly named calibration, by modifying the name in **New calibration name** edit box in the **New Calibration** dialog box. If a new calibration has been added to the **Calibration Library** file, the user should click on the **Save calibration library** button on the **Data Conversion** dialog box to ensure that the new calibration has been saved.

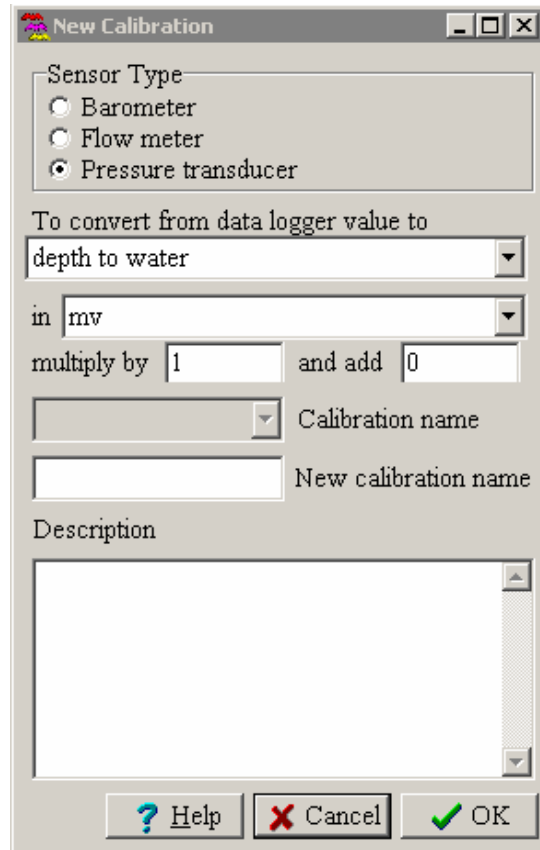



Figure 4. New Calibration dialog box.

A **Calibration Library** file has been prepared for the sensors that can be shipped with the Multifunction BAT³. Included in this file are calibrations for spare transducers, barometers and flow meters that may also be used with the Multifunction BAT³. This **Calibration Library** file is named **BAT3_LAB.cvl**, and it is included with the distribution of the BAT³ Analyzer. In setting up the **Data Conversion** dialog box, the user should check the serial numbers of the sensors attached to the data-acquisition equipment of the Multifunction BAT³ and choose the appropriate calibration name.

Units Conversion Calculator

A **Units Conversion Calculator** is supplied in the BAT³ Analyzer as a convenience to the user (fig. 5). The **Units Conversion Calculator** calculates the equivalent value for a specific parameter in different units. Conversions are available for length, volume, time, volumetric flow rate, pressure, transmissivity, hydraulic conductivity, specific storage, and inverse time. The calculated values can be copied into the system Clipboard, and then pasted into other applications

or other locations in the BAT³ Analyzer. For example, the calculated values can be pasted into appropriate cells in the **Model Interpretation** window. To use the **Units Conversion Calculator**, the user selects the menu item **Tools|Units Conversion** or clicks the **Units Conversion** button .

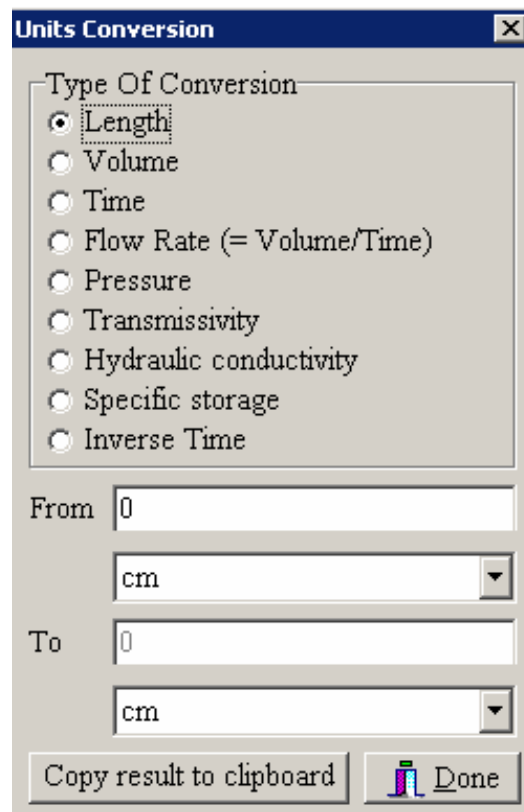



Figure 5. Units Conversion Calculator.

Calibrating Sensors

The BAT³ Analyzer can develop calibrations for sensors used with the Multifunction BAT³ by performing a linear correlation between the “raw” data collected with the data-acquisition equipment of the Multifunction BAT³ and independent check measurements, for example, independent measurements of flow rate, or independent measurements of the height of water above the transducer. Shapiro (2007) discusses the method of calibrating pressure transducers using the equipment supplied with the Multifunction BAT³. Performing the check measurements for conducting field calibrations of the pressure transducers is recommended to check that the transducers are operating properly and to ensure that the proper calibrations are applied to the transducer data in estimating hydraulic properties of the test interval (see section “Estimating Hydraulic Properties of a Test Interval” on page 25).

To perform a calibration of one of the sensors attached to the Multifunction BAT³, the user must have either have a **Raw Data** file or an **Interpreted Data** file open (see the section “Opening and Saving Data Files” on page 8). Calibrations can be conducted while testing is still being conducted and the BAT³ Analyzer is updating data that are displayed. Choosing the

Calibrate|**Calibrate** menu item or clicking the **Calibrate** button  opens the **Field Calibration** dialog box (fig. 6). The **Field Calibration** dialog box has two tabs, **Controls** and **Graph**. The **Controls** tab is the location where the raw data measured by the sensor are selected and the check measurements are entered. The **Controls** tab also displays the results of the least-squares estimate of the multiplier and offset of the linear calibration between the “raw” data and the check measurements. The correlation coefficient (r^2) on the **Controls** tab indicates the quality of the fit between the raw data measured by the sensor and the check measurements; a correlation coefficient equal to 1 indicates a perfect linear correlation between the raw data measured by the sensor and the check measurements (see Draper and Smith, 1968). The **Graph** tab displays a graph of the calibration showing the data points and a linear least-squares regression line between the “raw” data measured by the sensor and the check measurements. The chart of the calibration can be formatted using the **Format Chart** menu item on the top of the **Field Calibration** dialog box. Editing the chart attributes is conducted similarly to the editing of the charts in the sensor windows (see section “Formatting the Time Axis on Charts” on page 13). The chart image of the calibration can also be saved to a file using the **File**|**Save as Image** menu item on the top of the **Field Calibrations** dialog box. The chart of the calibration can also be printed (see section “Saving and Printing Chart Images” on page 14).

To perform a calibration of a particular sensor attached to the Multifunction BAT³, the user selects the sensor to calibrate in the **Field Calibration** dialog box. The user then chooses the observations times, at which check measurements have been performed. For example, a check measurement for calibrating a pressure transducer is the measurement of the height of water above the transducer at the same time the raw data has been collected by the data-acquisition equipment of the Multifunction BAT³ (see Shapiro 2007). In calibrating transducers, it is assumed that the depth to the transducer sensor below a given datum (such as the top of the borehole casing) is known, and the depth to water in the borehole below the same datum is measured (see Shapiro 2007). At least 2 check measurements must be made at different times with different values to perform a calibration, and it is best to perform multiple check measurements over the range of the transducer in performing the calibration.

In conducting a field calibration of a pressure transducer that measures absolute pressure, the calibration must correct for the barometric pressure. Checking the box on the **Field Calibration** dialog box to correct for barometric pressure requires the user to specify the calibration associated with the barometric sensor. A **Calibration Library** file can be loaded to the active memory of the BAT³ Analyzer using the **Load calibration library** button on the bottom of the **Field Calibration** dialog box. A calibration for the barometric sensor can be chosen from one of the calibrations in the **Calibration Library** file using the pull-down menu. Alternatively, the multiplier and offset for the barometer can be manually entered into the appropriate boxes on the **Field Calibration** dialog box. The correct units associated with the check measurements should be specified from the pull-down menu. Field calibrations for the flow meters and barometer can also be performed if check measurements for these sensors have been made.

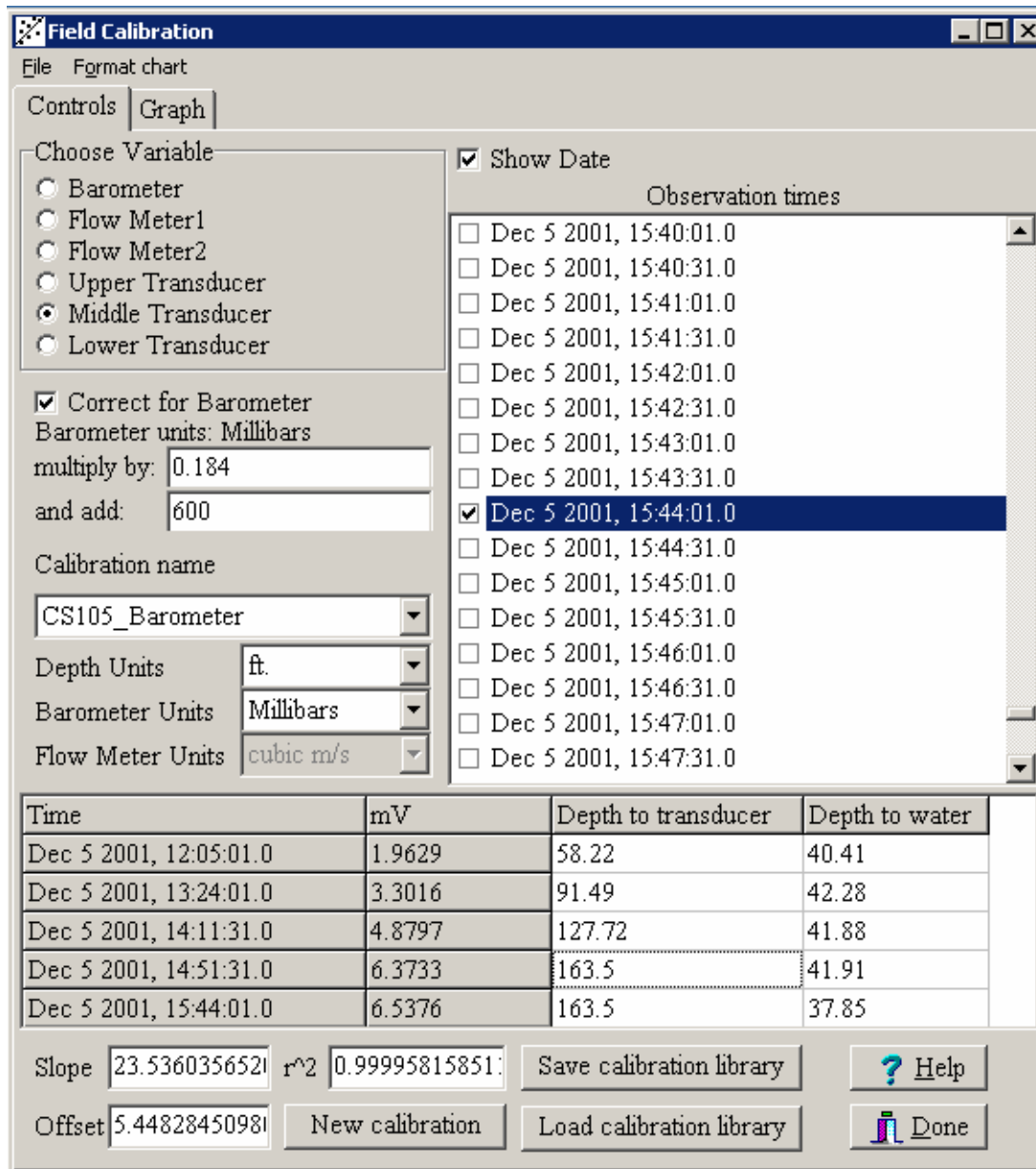


Figure 6. Field Calibration dialog box.

After the field calibration has been conducted in the **Field Calibration** dialog box, the calibration results can be stored by clicking the **New calibration** button. This operation opens the **New Calibration** dialog box where the multiplier and offset from the calibration are located in the appropriate edit boxes. The user will need to specify the calibration name and enter a brief description of the calibration and the sensor, and then click the **OK** button. This calibration can be saved in a **Calibration Library** file. If a **Calibration Library** file has been loaded, it will be appended to the **Calibration Library** file that has been loaded when the calibration library is saved. If a **Calibration Library** file has not been loaded, the new calibration can be saved to a new **Calibration Library** file (see section “Creating, Saving, and Loading a Calibration Library” on page 18).

The data used to calibrate the sensor can be saved to a **Calibration** file with the extension “cal” using the **File|Save** menu item in the **Field Calibration** dialog box. The structure of **Calibration** files is given in Appendix 5. The **Calibration** files only contain the data records from the **Raw Data** file that were used in performing the calibration. The **Calibration** files are useful in recording the underlying data that was used in creating a sensor calibration, which may or may not have been stored in a calibration library. **Calibration** files can be reopened by selecting **File|Open** in the **Field Calibration** dialog box to view the underlying data used in performing a calibration. This operation will provide a list of only those data records used in performing the calibration. The **Raw Data** file that was used in creating the calibration does not need to be opened by the BAT³ Analyzer to observe the records used in the calibration; however, if a barometric correction was used in the calibration of a pressure transducer and that barometric calibration was chosen from a **Calibration Library** file, the **Calibration Library** file will need to be loaded into the BAT³ Analyzer by selecting the **Load calibration library** button on the **Field Calibration** dialog box.

Example of Calibrating a Transducer

The following example of calibrating a transducer is drawn from data collected using the Multifunction BAT³. The data file **01_339A.DAT** distributed with the BAT³ Analyzer is used in this example and it is assumed that the user has opened this **Raw Data** file before performing the steps listed in this section (see section “Opening and Saving Data Files” on page 8). During testing with the Multifunction BAT³, check measurements of depth to water were made at selected times for the purpose of conducting a field calibration of the pressure transducers. The times and the associated check measurements are listed in table 2.

Table 2. Check measurements for pressure transducers during testing with the Multifunction BAT3.

Date	Time	Depth to Transducer* (feet)	Depth to Water* (feet)
5-Dec-2001	12:05:01	58.22	40.41
5-Dec-2001	13:24:01	91.49	42.28
5-Dec-2001	14:11:31	127.72	41.88
5-Dec-2001	14:51:31	163.5	41.91
5-Dec-2001	15:44:01	163.5	37.85

*depth measured below top of surface casing extending above land surface
The raw data from the transducers collected during these check measurements are given in data file 01_339A.DAT.

Using the check measurements given in table 2 and the raw data in the file **01_339A.DAT**, the middle transducer is calibrated by conducting the following steps.

1. Select the **Calibrate|Calibrate** menu item in the BAT³ Analyzer.
2. Select Middle Transducer under Choose Variable.
3. In the list labeled **Observation times**, check the boxes associated with times given in table 2. The **Show Date** check box can be checked to show the full date of the **Observation times**.
4. Check the box labeled **Correct for Barometer**; the pressure transducer being calibrated measures absolute pressure.


5. Load the conversion library **BAT3_Lab.cvl** by moving the cursor to the **Load calibration library** button and clicking the left mouse button.
6. Select the stored calibration for the barometer from the pull-down menu under the calibrations for the barometer; the barometer used during this data collection was named CS105_Barometer.
7. Change the **Depth Units** to feet using the pull-down menu.
8. Enter values for the **Depth to transducer** and **Depth to water** for each check measurement listed in table 2.
9. Click on the **Graph** tab to display a plot of the calibration data.
10. Make a note of the slope (23.536) and offset (5.448) on the **Field Calibration** dialog box.
11. (Optional) Create a new calibration by clicking the **New calibration** button and fill in the **New calibration name** and the **Description** of the transducer on the **New Calibration** dialog box, and then click the **OK** button.
12. Click on **File|Save** menu item and choose a file name and a disk location to save the calibration data.

The pressure transducer being calibrated in the above example is a Druck PDCR 1830 absolute pressure transducer (Serial Number 992057). The laboratory calibration associated with this transducer resulted in a multiplier of 23.398 and an offset of -0.413 to convert measured responses of the transducer in millivolts to the height of water (measured in feet) above the transducer; this laboratory calibration is given in the file **BAT3_Lab.cvl**. The multiplier associated with the field calibration for this transducer varies by less than one percent in comparison to the laboratory value. The offset associated with the field calibration, however, is significantly different than the laboratory offset. This arises because the exact depth of the transducer below the datum during the field calibration was not used. The length of the pipe used to lower the Multifunction BAT³ to a given location in the borehole was used as an estimate of the depth of the transducer below the datum (top of the surface casing). The exact location of the transducer in the downhole equipment of the Multifunction BAT³ could be used in these calculations to achieve a more exact value of the offset for the pressure transducer. The offset, however, is not crucial in estimating the hydraulic properties of the test interval from fluid pressure responses measured during testing with the Multifunction BAT³. The differences in fluid pressure responses taken at different times are used in these calculations, and consequently, the offset in the field calibration of the transducer is subtracted out of these calculations. Further information about the procedures for conducting a field calibration of pressure transducers using the Multifunction BAT³ is given in Shapiro (2007).

Estimating Hydraulic Properties of a Test Interval

The **Model Parameters** dialog box is used to estimate hydraulic properties from the sensor responses recorded during testing with the Multifunction BAT³. Fluid pressure responses from the middle-zone transducer (the fluid pressure transducer in the test interval) will be used to estimate hydraulic properties associated with the test interval. The user can identify the type of hydraulic test (fluid injection, pumping, or slug test) that was conducted in the test interval and choose various hydrogeologic conceptual models of the formation to estimate the parameter values in those conceptual models that best reproduce the measured fluid pressure responses. Plots of the model results versus the measured fluid responses in the test interval are generated and the user can alter

the values of the model parameters to achieve an acceptable fit with the measured fluid pressure responses.

Selecting the **Tools|Model Parameters** menu item or the **Model Parameters** button  opens the **Model Parameters** dialog box (fig. 7). Prior to using the **Model Parameters** dialog box, the “raw” data must be converted to physically meaningful units using the **Data Conversion** dialog box (see the section “Applying Calibrations to Raw Data” on page 15). The **Model Parameters** dialog box has 4 tabs, **Model Choices**, **Known Values**, **Model Parameters**, and **Plot Controls**.

On the **Model Choices** tab, the user selects the **Test type**, the hydrogeologic conceptual **Model**, the **Test interval type**, and **Model controls** associated with the starting time of the model results. The **Test type** can be **Pumping**, **Fluid injection**, or a **Slug test**. For the interpretation of slug tests, the transient fluid pressure responses are interpreted in a formation that is assumed to behave analogously to a porous medium. For the pumping and fluid-injection tests, the user can choose one of the following hydrogeologic conceptual models,

- Steady-state radial flow
- Transient radial flow
- Transient radial flow with quasi-steady leakage
- Transient radial flow in a dual porosity aquifer

The first three choices assume the fluid pressure response in the formation behaves as a porous medium. The final choice assumes the formation behaves as a dual porosity aquifer. The assumptions and the mathematical formulation for the interpretation of hydraulic tests conducted with these hydrogeologic conceptual models are given in Appendix 7. With the exception of the steady-state radial flow model, the **Test interval type** can be assumed to be **Packed off/Pressurized interval** or an **Open interval with free surface**. For example, if both packers of the Multifunction BAT³ are inflated, and the test interval is fluid filled, the test interval will be pressurized. Alternatively, the Multifunction BAT³ can be used to test with none or only one of the packers inflated (Shapiro, 2007). If only the bottom packer is inflated, then the test interval in the borehole will have a free water surface. The hydraulic responses in a borehole with a free water surface will be different from those in a pressurized interval (see Appendix 7).

The **Model controls** on the **Model Choices** tab defines the starting time of the simulation of the model results. The starting time is entered as the (base 10) logarithm of the starting time in units of seconds. For example, if the starting time of the model results is chosen to be 1 second, the value of zero (0) is entered; the base 10 logarithm of 1 is equal to 0. Under **Model controls**, the user also enters the **Number of evaluation points per log cycle**. This is the number of points in time at which the model results are evaluated. For example, choosing a value of 10 for this control will result in the model solution being evaluated at 10 evenly spaced points between 1 and 10 seconds, 10 and 100 seconds, and so forth.

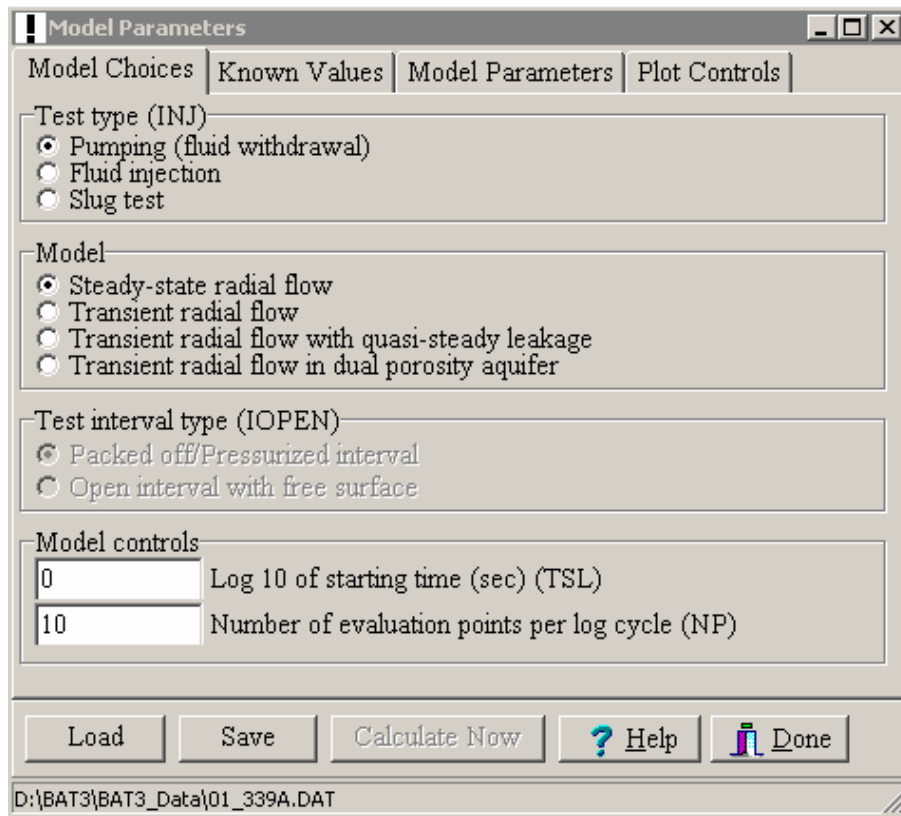




Figure 7. Model Choices tab of the Model Parameters dialog box.

On the **Known Values** tab of the **Model Parameters** dialog box, the user enters values for physical information that need to be specified for evaluating the model results associated with the test type and hydrogeologic conceptual model of the formation (fig. 8). The user must enter values in the boxes that are highlighted in red. The boxes that are gray are inactive for the choice of the **Test type** and **Model** selected on the **Model Choices** tab. The user may need to enter information into active boxes using digital information from the **Data Display** window. For example, values of the **Volumetric pumping rate** or **Volumetric injection rate**, and the **Initial depth to water**, **Initial height of water above the transducer**, or **Initial hydraulic head above datum** can be selected and copied from cells in the **Data Display** window. For example, the user would use the following steps to copy digital data from the **Data Display** window:

1. Make the **Data Display** window the active window by moving the cursor over the **Data Display** window and clicking with the left mouse button. This action may hide the **Model Parameters** dialog box behind the **BAT3** window. To return to the **Model Parameters** dialog box, the user should click on the **Model Parameters** button .
2. On the **Data Display** window, navigate to the time of the data record of interest for the volumetric flow rate or middle-zone transducer; it is assumed that the responses of the flow meters and middle-zone transducer have been converted to physically meaningful units using the **Data Conversion** dialog box.
3. Highlight the cell in the **Data Display** window by moving the cursor over the cell and double clicking with the left mouse button.

4. Use **control-c** to copy the contents of the cell.
5. Make the **Model Parameters** dialog the active window by moving the cursor over the dialog box and clicking with the left mouse button, or clicking on the **Model Parameters** button . Then click on the **Known Values** tab to make it the active window.
6. Move the cursor over the data entry box of interest and click with the left mouse button, and then use **control-v** to paste the digital record from the **Data Display** window.

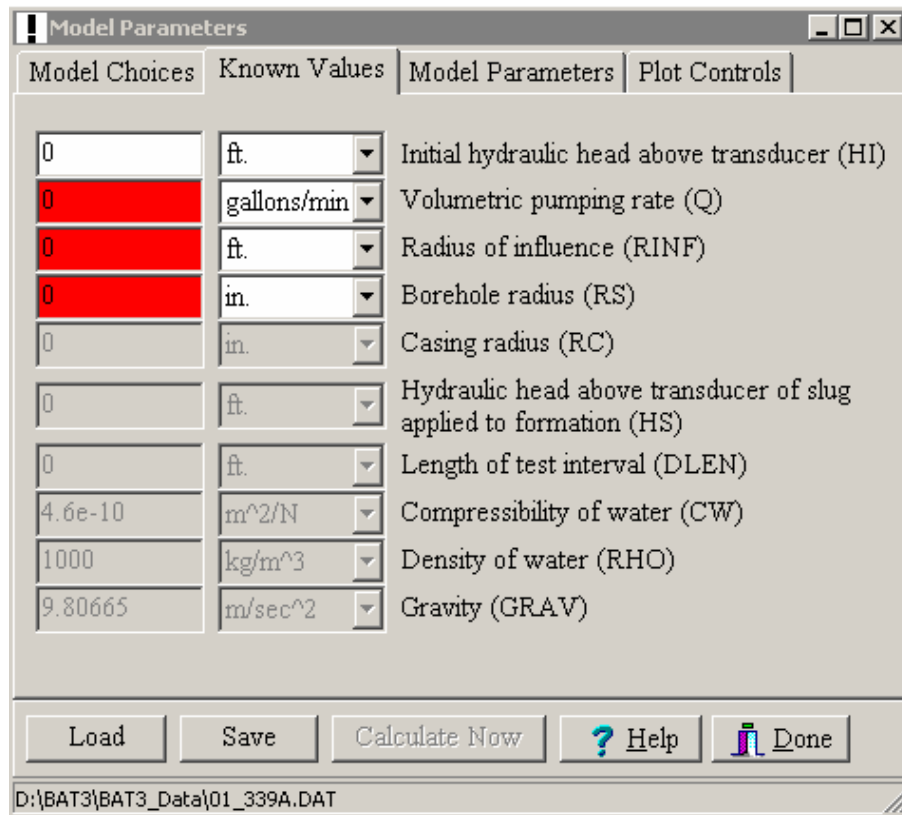


Figure 8. Known Values tab of the Model Parameters dialog box.

The units for all of the information shown on the **Known Values** tab must also be specified. Pull-down menus are used to specify the units of the physical information entered on this tab. The units of the various terms do not have to be consistent; the BAT³ Analyzer will convert the values into consistent units prior to making the calculations associated with the model results.

On the **Model Parameters** tab (fig. 9) of the **Model Parameters** dialog box, the user specifies the assumed values of the parameters associated with the hydrogeologic conceptual model selected on the **Model Choices** tab. Only those parameters that are associated with the selected hydrogeologic conceptual model are active. The other data entry boxes are grayed, and their contents cannot be altered. The units for the parameter values on the **Model Parameters** tab must also be specified. Pull-down menus are used to specify the units of the parameters entered on this tab. The units of the parameters do not have to be consistent; the BAT³ Analyzer will convert these values into consistent units prior to making the calculations associated with the model results.

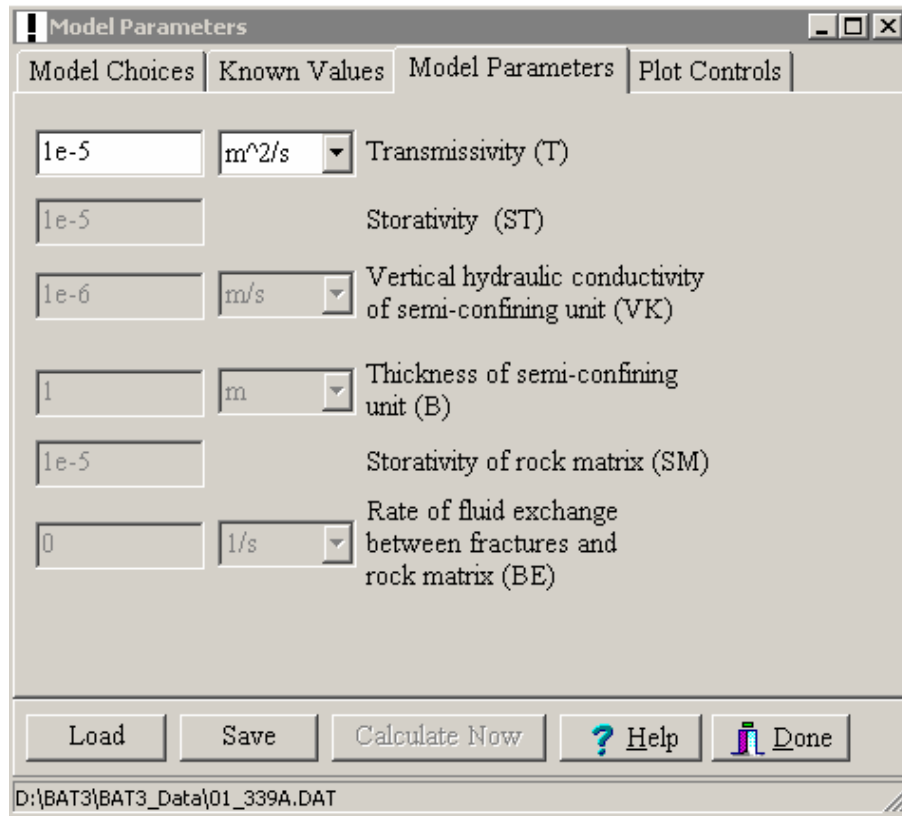


Figure 9. Model Parameters tab of the Model Parameters dialog box.

After the physical information and model parameters have been specified for the selected hydrogeologic conceptual model, information on the **Plot Controls** tab of the **Model Parameters** dialog box can be specified.

Entries on the **Plot Controls** tab of the **Model Parameters** dialog box are used to specify the starting time and duration of the hydraulic test (fig. 10). A calendar is used to specify the year, month, day, and time associated with the starting time of the test, and the duration of the test is specified in minutes. These entries are used to select the fluid pressure responses of the middle-zone transducer from the data file opened by the BAT³ Analyzer for comparison with the calculated results of the selected hydrogeologic model and the specified model parameters.

For the hydrogeologic conceptual models that consider transient fluid pressure responses, boxes can be checked on the **Plot Controls** tab to specify the method of displaying the calculated model results and the measured fluid pressure responses. For example, the (horizontal) time axis can be plotted as the logarithm of the elapsed time from the start of the hydraulic test. Also, the vertical axis can be plotted as the logarithm of the fluid pressure response (for example, height of water above the transducer, depth to water below a given datum, or the height of water above a given datum). If these boxes on the **Plot Controls** tab are not checked, the horizontal and vertical axes are plotted on a linear scale. For transient fluid pressure responses, the drawdown can also be plotted by checking the appropriate box; drawdown is the difference between the fluid pressure response at a given time during the hydraulic test and the fluid pressure response at the start of the test.

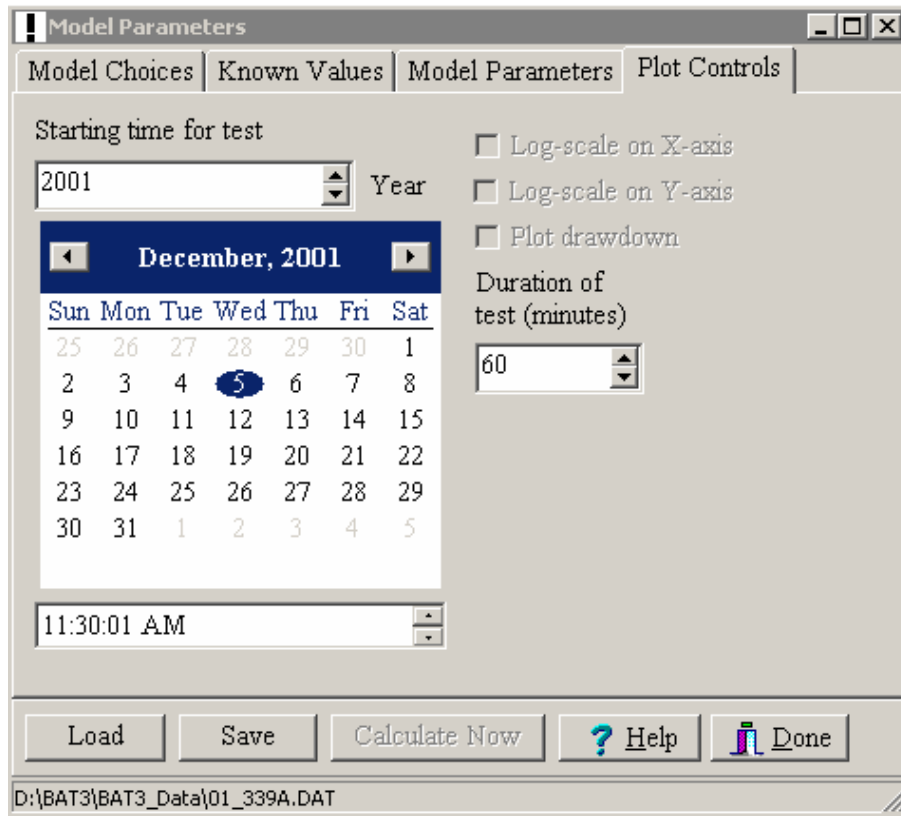


Figure 10. Plot Controls tab of the Model Parameters dialog box.

If the physical information in the **Known Values** tab has been entered, the **Calculate Now** button on the bottom of the **Model Parameters** dialog is active. Moving the cursor over the **Calculate Now** button and clicking with the left mouse button will open a **Model Values** chart that displays the calculated results of the hydrogeologic conceptual model for the specified parameter values and the fluid pressure responses from the middle-zone transducer. This chart can be edited and printed by clicking the left mouse button on the **Format Chart** menu item, which will open a dialog box similar to that used in editing and printing charts of the various sensor windows (see the section “Formatting Other Chart Attributes” on page 14). The chart image can also be saved to a file using the **Save as Image** menu item.

Depending on the comparison between the calculated model results and the measured responses of the middle-zone transducer, the user can choose to return to the **Model Parameters** tab and alter the parameter values to adjust the calculated model results. Upon changing the model parameters, or any of the other physical information, the user needs to click on the **Calculate Now** button to update the **Model Values** chart. Thus, the BAT³ Analyzer uses a trial and error method of fitting model results and measured fluid pressure responses.

The user can save the selections in the **Model Parameters** dialog to a **Parameter Values** file. **Parameter Values** files have the file extension “pv”. The **Parameter Values** file is an ASCII file with the structure shown in Appendix 6. In the **Parameter Values** file, the selections and entries made in the tabs on the **Model Parameters** dialog are saved. Saving information in **Parameter Values** files allows the user to chronicle the various interpretations that are made from

the data recorded with the Multifunction BAT³. Moving the cursor over the **Save** button and clicking with the left mouse button opens a dialog box, where the user specifies the name and location of the **Parameter Values** file.

The **Parameter Values** file includes a listing of the X and Y values plotted on the **Model Values** chart for both the calculated model results and the measured responses of the middle-zone transducer. The listing provided in this file can be copied into other software packages for the purpose of plotting the model results and the middle-transducer responses.

Clicking the left mouse button on the **Load** button of the **Model Parameters** dialog opens a dialog box for the user to choose a **Parameter Values** file. The BAT³ Analyzer will read the information to populate the selections and entries in the **Model Choices**, **Known Values**, **Model Parameters**, and **Plot Controls** tabs of the **Model Parameters** dialog box. Clicking the **Calculate Now** button will then display the **Model Values** chart with the calculated model results. If the user wishes for the measured transducer responses to be displayed on the **Model Values** chart, the user will need to open (if it is not open already) the **Raw data** file and apply the sensor calibrations or open the **Interpreted data** file, from which the **Parameter Values** file was originally generated (see the section “Opening and Saving Data Files” on page 8).

Example of Estimating Hydraulic Properties of a Test Interval

This section illustrates the capabilities of the BAT³ Analyzer in interpreting the fluid pressure responses from fluid-injection tests conducted with the Multifunction BAT³. In this example, transmissivity is estimated using the assumption that the hydraulic responses in the test interval can be interpreted with a steady-state radial flow model. A detailed explanation of the limitations and assumptions of applying the steady-state radial flow model in the interpretation of fluid-injection tests can be found in Shapiro and Hsieh (1998). Appendix 7 also provides information about the mathematical development and assumptions underlying interpretations of fluid-injection tests using a steady-state radial flow model. It is beyond the scope of this report to consider the interpretation of fluid pressure responses with the hydrogeologic conceptual models that consider transient fluid pressure responses. The user is referred to authors such as Lohman (1979), Streltsova (1988), and Kruseman and de Ridder (1991) for detailed explanations of the methods of interpreting transient fluid pressure responses using the various hydrogeologic conceptual models. Appendix 7 also provides information about the mathematical development and assumptions underlying the hydrogeologic conceptual models that are available for interpretation within the BAT³ Analyzer.

The examples in this section use files that are distributed with the BAT³ Analyzer. These files are a **Raw Data** file, **01_339A.DAT**, and a **Setup** file, **01_339_inj.suf**. In this example, testing with the Multifunction BAT³ has been conducted with a set of sensors; the listing of the sensor calibrations has been compiled in the **Setup** file, **01_339_inj.suf**. After starting the BAT³ Analyzer, the first step is to load the **Setup** file. This is accomplished by performing the following steps:

1. Select Calibrate|Chose Calibrations.
2. Click the Load setup button and select the file 01_339_inj.suf.
3. Click the Done button.

The next step is to load the **Raw Data** file containing the data collected with the data-acquisition system of the Multifunction BAT³. This data has already been collected, and the data file is being viewed after testing has been completed; however, the interpretation of the fluid pressure responses can also be conducted as downhole testing is still being conducted. The following steps are performed to open the **Raw Data** file:


4. Select **File|Open** and select the file **01_339A.DAT**. The user will be prompted to either retain the existing calibrations or reset them to their default values. Click on **No** to retain the calibrations for the sensors loaded in steps 1-3 given above.
5. All the data in the **Raw Data** file will be plotted on the sensor windows. The **Temperature** and **Barometric Pressure** can be closed to allow more space for the other sensor windows in the **BAT3** window by selecting **Graphs|Barometer** and **Graphs|Temperature** menu items, or by closing these sensor windows clicking on the close button  in the upper right corner of these windows.

Table 3 provides a list and description of the tests that were included in the **Raw Data** file **01_339A.DAT**. In the collection of this data file, five (5) fluid-injection tests were conducted. In the remainder of this section, the interpretation of only one of the fluid-injection tests is considered. Information on all five of the fluid-injection tests reported in the **Raw Data** file, however, is included in table 3 along with the results of the estimation of the transmissivity of the test interval using the assumption of a steady-state radial flow model to interpret the fluid pressure responses in the test interval. The description of conducting fluid-injection tests with the Multifunction BAT³ is described in Shapiro (2007).

The interpretation of the fluid-injection test used in this example was conducted during the time interval 15:33:00 to 15:41:00 on December 5, 2001. Other information pertaining to the operation of this test is given in table 3. To interpret this test, the user must first focus on the data associated with this particular test. This is conducted by plotting the data on the sensor windows so that only the data from this test is viewed. The following steps are used to show the data associated with this test:

6. Select **Format|Starting Time / Update Interval** menu item.
7. Select **Specify starting time and duration**.
8. Set the starting time to 3:30 PM and the Number of minutes to plot to 15 minutes and then click the OK button. The data should look similar to figure 11.

Table 3. Fluid injection tests recorded in the Raw Data file 01_339A.DAT.

[TOC is top of casing; ft²/day is square feet per day; borehole radius is 3 inches]

Date	5-Dec-2001	5-Dec-2001	5-Dec-2001	5-Dec-2001	5-Dec-2001
Julian Day	339	339	339	339	339
Test Interval Top: (ft below TOC)	58.22	91.49	127.72	163.50	163.5
Test Interval Bottom: (ft below TOC)	92.00	125.25	161.50	197.28	241 (Bottom of borehole)
Time: Start Packer Inflation	12:43:00	13:25:00	14:13:00	15:27:00	Top packer inflated from previous test.
Time: Close Transducer Bleed Valves	12:47:00	13:30:00	14:16:30	15:29:00	15:49:00
Test Type	Fluid Injection	Fluid Injection	Fluid Injection	Fluid Injection	Fluid Injection
Time: Start Fluid Injection	12:55:00	13:34:00	14:23:00	15:33:00	15:52:00
Time: End Fluid Injection	13:00:00	13:54:00	14:34:00	15:41:00	16:01:30
Time: Open Transducer Bleed Valves	13:01:00	13:55:00	14:35:00	15:42:00	16:02:00
Time: Deflate packers	13:02:00	13:56:00	14:36:00	15:45:00 (Deflate bottom packer only)	16:03:00 (Deflate top packer)
Transmissivity: ft²/day	<10 ⁻⁴	9.3 x 10 ⁻²	7.4 x 10 ⁻²	4.8	14.0
Comment:	Start injection test with Flow meter 1. Switch to Flow meter 2 at 12:57.	Start injection test with Flow meter 1. Switch to Flow meter 2 at 13:44	Start injection test with Flow meter 1. Switch to Flow meter 2 at 14:25	Start injection with Flow meter 1.	Start injection with Flow meter 1. Only top packer inflated during test.
Interpretation:	No detectable flow – minimum transmissivity assigned to test interval.	Estimate transmissivity using steady-state radial flow and responses from Flow meter 2. Radius of influence = 15 ft.	Estimate transmissivity using steady-state radial flow and responses from Flow meter 2. Radius of influence = 15 ft.	Estimate transmissivity using steady-state radial flow and responses from Flow meter 1. Radius of influence = 15 ft.	Estimate transmissivity using steady-state radial flow and responses from Flow meter 1. Radius of influence = 15 ft.

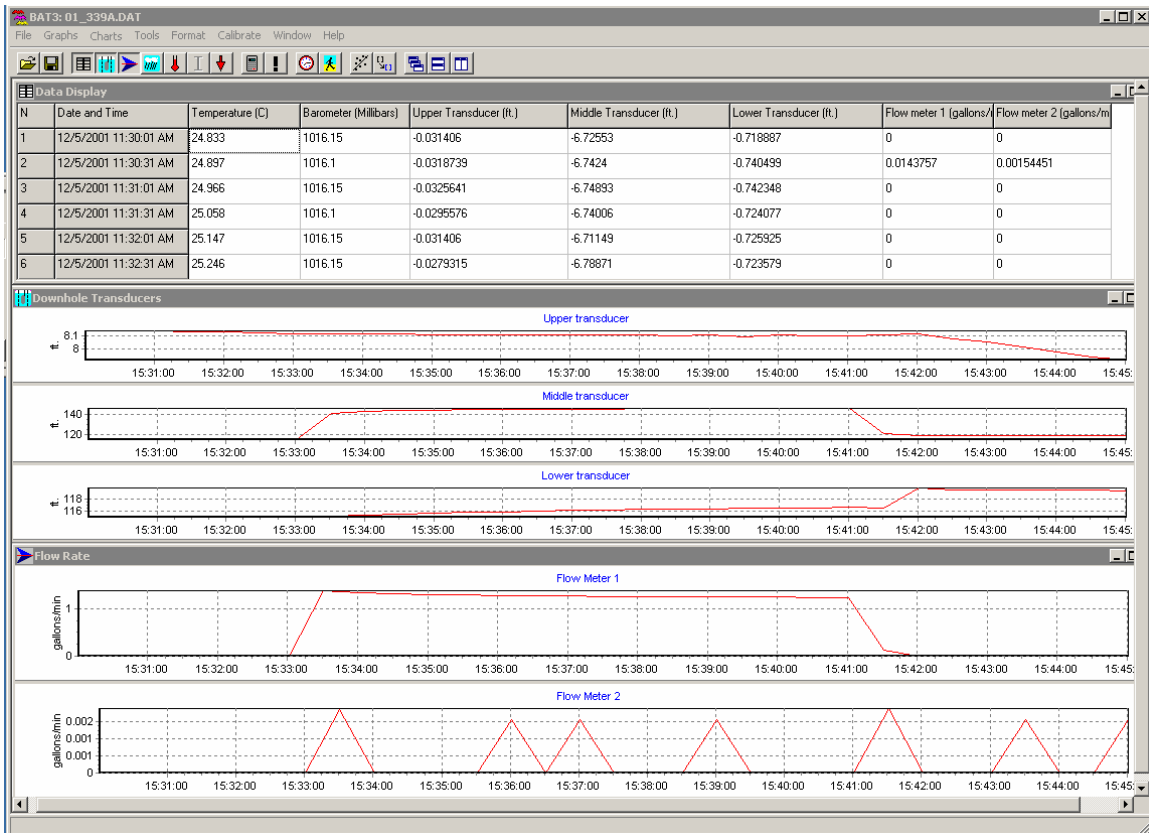


Figure 11. BAT3 window with Data Display, Downhole Transducers, and Flow Rate windows for example of estimating hydraulic properties from a fluid-injection test.

The flow rate was recorded with Flow meter 1, which clearly shows when the fluid-injection test was started and ended. The responses shown on the chart for Flow meter 2 are intermittent noise in the data record. Also, at the start of the fluid-injection test, the middle transducer shows an abrupt increase due to the fluid entering the test interval. There is also a slight rise in the fluid pressure monitored below the bottom packer in the Lower Transducer; however, the magnitude of the pressure rise in the bottom interval is small in comparison to the increase in fluid pressure in the test interval. The user may choose to edit the plots of the pressure transducer using the **Format|Format Chart** menu item.

The pressure transducer and flow meter responses shown on the sensor windows for the test under consideration (fig. 11) can be interpreted by using a steady-state radial flow model of the fractures intersecting the test interval. The steady-state model is appropriate to interpret this data because both the flow rate and the fluid pressure in the test interval are relatively stable over the entire extent of the test. There is some degradation in the flow rate as the test proceeds, but for the purpose of estimating the hydraulic properties of the test interval, the assumption of a steady-state flow regime provides an estimate of the magnitude of the transmissivity.

The following steps are conducted to interpret this fluid-injection test:

9. Select the **Tools|Model Parameters** menu item to open the **Model Parameters** dialog box.

10. Select the **Model Choices** tab.
11. Under **Test type**, select **Fluid injection**.
12. Under **Model**, select **Steady-state radial flow**.
13. For **Model controls**, the default values can be used, that is, 0 for **Log 10 of starting time**, and 10 for **Number of evaluation points per log cycle**.
14. Select the **Known Values** tab.
15. For the **Radius of influence**, enter 15 ft. The radius of influence is the radial distance from the injection interval where it is assumed that there is no hydraulic response from fluid injection. Other values of the radius of influence can also be assumed. The user can conduct other interpretations of the fluid-injection test data using different estimates of the radius of influence and observe the change in the transmissivity that is estimated.
16. For the **Borehole radius**, enter 3 inches; this is the radius of the borehole in the test interval.

The other parameters that need to be entered on the **Known Values** tab of the **Model Parameters** dialog box are the **Initial height of water above transducer**, and the **Volumetric injection rate**. Values for these parameters can be copied from the **Data Display** window and pasted into the appropriate boxes on the **Known Values** tab. The following steps are conducted to access the information from the **Data Display** window:

17. Move the cursor over the **Data Display** window, and click the left mouse button to make it the active window, and use the scroll bars to navigate to the starting time of the test (15:33:00 on December 5, 2001). Another method of navigating to this data on the **Data Display** window is to make the **Downhole Transducers** or **Flow Rate** window the active window, and then move the cursor over a data point on the chart at the desired time and clicking with the left mouse button.
18. Select the cell on the **Data Display** window associated with the middle transducer at the time 12/5/2001 3:33:01 PM. The value of this cell is 114.686 ft, and represents the initial height of water above the transducer prior to the fluid-injection test. The user may wish to scroll on the **Data Display** window to view the responses of the Middle Transducer at earlier times to assess if this value is a stable starting point for the fluid injection test. The value in the cell (12/5/2001 3:33:01 PM) can be copied by first moving the cursor over the cell and double clicking with the left mouse button, and then using **control-c** to copy the cell value to the computer clipboard.
19. Return to the **Model Parameters** dialog box by choosing the **Tools|Model Parameters** menu item and then moving the cursor over the data entry box for the **Initial height of water above transducer** on the **Known Values** tab and clicking with the left mouse button.
20. Paste the value from the middle transducer into the data entry box by pressing **control-v**.
21. Steps similar to 17-21 are used to copy the value of the fluid injection rate and paste it in the data entry box on the **Known Values** tab of the **Model Parameters** dialog box. The time associated with the fluid injection rate that should be chosen for the interpretation of this test should be prior to the completion of the test. The value at the time 12/5/2001 3:41:01 PM is 1.23155 gallons per minute was collected immediately prior to the termination of the test.

On the **Model Parameters** tab of the **Model Parameters** dialog box, the default value of the **Transmissivity** can be used as a first estimate in matching the responses of the middle zone

transducer with the modeled results from the steady-state radial flow model. The remaining controls that need to be specified are located on the **Plot Controls** tab of the **Model Parameters** dialog box. To continue with the interpretation of the fluid-injection test, the following steps are conducted:

22. Select the **Plot Controls** tab and specify the starting time of the test. The **Year** is specified in the data entry box, and the calendar is used to specify the date. The time of the start of the test should be specified as 3:33:00 PM.
23. The **Duration of test** can be set 10 minutes.
24. Move the cursor over the **Calculate Now** button and click with the left mouse button.
25. The **Model Values** chart appears in which the results of the steady-state radial flow model is displayed along with the responses of the middle transducer as a function of the elapsed time from the start of the test.

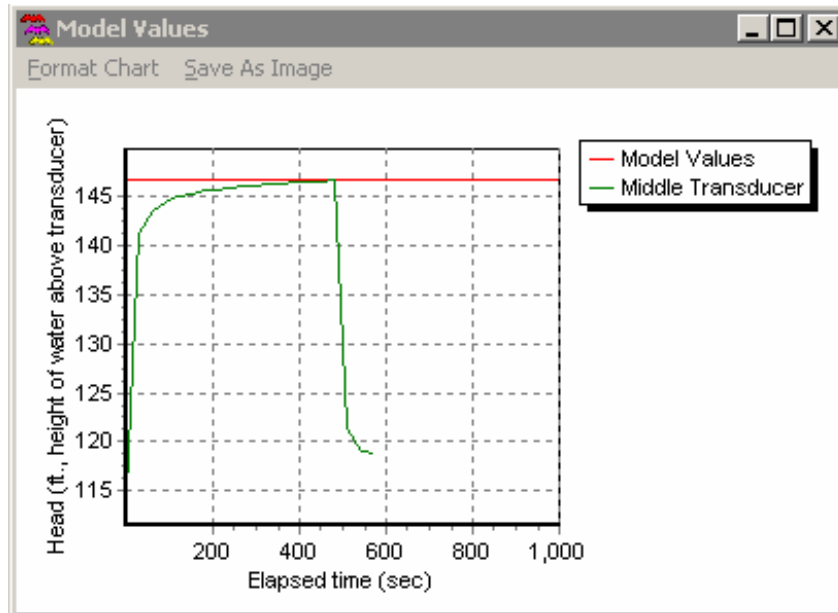



Figure 12. Model Values chart showing results from a steady-state radial flow model and measured responses of the middle-zone transducer from a fluid-injection test.


The default value of the **Transmissivity** on the **Model Parameters** tab does not provide a suitable fit with the measured responses of the middle zone transducer. The user can return to the **Model Parameters** tab and adjust the value of the **Transmissivity** and then click on the **Calculate Now** button to update the model results. The model results are constant with time because a steady-state flow model is being employed. The transmissivity should be adjusted so that the measured responses of the middle transducer are nearly the same as the steady-state model results. Figure 12 shows a suitable fit between the model results and the middle zone transducer. The value of the transmissivity that provided the model results shown in figure 12 was 5.6×10^{-5} square feet per second (ft^2/s). This value can be converted to other units using the Units Conversion Calculator (see the section “Units Conversion Calculator” on page 20). In addition, information from the comparison of the model results and the responses of the middle zone transducer can be saved to a

file in a **Parameter Values** file (see the section “Estimating Hydraulic Properties of a Test Interval” on page 25).

Predicting Hydraulic Responses

It is often advantageous to use a model of aquifer test responses prior to conducting the actual aquifer test to ascertain an estimate of the likely change in the hydraulic head in the test interval. Such modeling exercises are useful, for example, in designing pumping rates for geochemical sampling, provided that estimates of the hydraulic properties of the test interval are available.

The BAT³ Analyzer has the capability of modeling the hydraulic responses associated with an assumed type of hydraulic test, hydrogeologic conceptual model of the formation, and hydraulic properties, in the absence of data from the test interval. The **Model Parameters** dialog box can be used to calculate modeled hydraulic responses without opening either a **Raw Data** file or an **Interpreted Data** file. The user, however, must first define physically meaningful units for the middle zone transducer in the **Data Conversions** dialog box. This is necessary to define the units in which the hydraulic responses will be calculated in the **Model Parameters** dialog box. The user must first open the **Data Conversions** dialog box by either using the **Calibrate|Choose Calibrations** menu item or clicking on the **Choose Calibrations** button . The user must specify the **Units for display in Transducers** in units other than millivolts. The user must then select the **Middle Transducer** tab and specify the datum associated with measurements of the middle transducer and the units of conversion for the middle transducer in units other than millivolts. The multiplier and offset for the middle transducer do not have to be changed from the default values, of 1 and 0, respectively, because no data are being interpreted.

After closing the **Data Conversions** dialog box, the user should open the **Model Parameters** dialog box by either choosing the **Tools|Model Parameters** menu item or clicking on the **Model Parameters** button . The user can then select the **Test type**, **Model**, and other physical and control parameters on the **Model Choices**, **Known Values**, **Model Parameters**, and **Plot Controls** tabs. On the **Plot Controls** tab, the starting time for the test does not have to be specified in calculating the hydraulic responses, because no data are being used for comparison; however, the **Duration of Test** should be specified, as this value will dictate the time frame over which the model results are calculated. Clicking on the **Calculate Now** button will open the **Model Values** chart showing the model results. Information from the **Model Parameters** dialog box and the model results can be saved to a file in a **Parameter Values** file (see the section “Estimating Hydraulic Properties of a Test Interval” on page 25) by clicking on the **Save** button.

Acknowledgments

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Shapiro, A. M., and Hsieh, P. A., 1998, How good are estimates of transmissivity from slug tests in fractured rock?: *Ground Water*, v. 36, no. 1, p. 37-48.

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Appendix 1: File Structure of the Raw Data File (*.dat)

A **Raw Data** file generated by the data-acquisition equipment of the Multifunction BAT³ is an ASCII text file that contains the responses of the sensors attached to the Multifunction BAT³ during testing. In each line of a raw data file there are 12 entries, referred to as columns, which are separated by commas. The columns in each line of the raw data file 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

Example

```
108,2001,339,1240,.99999,32.599,2255.7,3.4659,2.1989,2.2197,356.43,0
108,2001,339,1240,31,32.644,2255.6,3.4654,2.052,2.0744,62.799,11.1
108,2001,339,1241,.99999,32.678,2255.6,3.4654,2.0168,2.0401,0,0
108,2001,339,1241,31,32.713,2255.9,3.4656,1.9942,2.0151,0,0
108,2001,339,1242,.99999,32.747,2255.2,3.4652,1.9735,1.9948,0,0
108,2001,339,1242,31,32.783,2255.5,3.4654,1.9735,1.9955,0,0
108,2001,339,1243,.99999,32.826,2255.2,3.4646,1.9723,1.9954,0,0
108,2001,339,1243,31,32.868,2255.2,3.4779,2.1096,2.0221,0,0
108,2001,339,1244,.99999,32.905,2255.2,3.4856,2.0031,2.007,0,0
108,2001,339,1244,31,32.939,2255.2,3.4861,1.985,2.0056,0,0
108,2001,339,1245,.99999,32.973,2255.1,3.4871,1.9847,2.0046,0,.03333
108,2001,339,1245,31,33.018,2255.1,3.4873,1.9851,2.0056,0,0
108,2001,339,1246,.99999,33.044,2255.1,3.4873,1.9855,2.0058,0,0
108,2001,339,1246,31,33.071,2255.1,3.4874,1.9846,2.005,0,0
108,2001,339,1247,.99999,33.106,2255.1,3.4869,1.9841,2.0055,0,0
108,2001,339,1247,31,33.123,2255.1,3.4868,1.9981,1.9675,0,0
108,2001,339,1248,.99999,33.159,2254.7,3.4868,2.0085,1.9621,0,0
108,2001,339,1248,31,33.185,2255,3.487,2.0172,1.9556,0,0
108,2001,339,1249,.99999,33.221,2255,3.4873,2.0262,1.9512,0,0
108,2001,339,1249,31,33.247,2254.6,3.4869,2.0306,1.9469,0,0
```

Appendix 2: File Structure for the Interpreted Data File (*.idf)

An **Interpreted Data** file is an ASCII text file that contains both the raw data and the interpretations of those data to physically meaningful values using calibrations for the sensors that are used by the Multifunction BAT³ during testing.

Line 1: 'Program = Bat3'
Line 2: 'Program Version = ' [version]
Line 3: 'File type = Interpreted data'
Line 4: [number of lines required to read the setup]
Line 5: 'comboBarometerUnits'
Line 6: [Display units for Barometer]
Line 7: 'comboFlowUnits'
Line 8: [Display units for flow meters]
Line 9: 'comboTransducerUnits'
Line 10: [Display units for pressure transducers]
Line 11: [Conversion name for Barometer]
Line 12: [Conversion description for Barometer]
Line 13: [Conversion slope for Barometer]
Line 14: [Conversion offset for Barometer]
Line 15: [Conversion type for Barometer]
Line 16: [Calculated units for Barometer]
Line 17: [Conversion name for Flow meter 1]
Line 18: [Conversion description for Flow meter 1]
Line 19: [Conversion slope for Flow meter 1]
Line 20: [Conversion offset for Flow meter 1]
Line 21: [Conversion type for Flow meter 1]
Line 22: [Calculated units for Flow meter 1]
Line 23: [Conversion name for Flow meter 2]
Line 24: [Conversion description for Flow meter 2]
Line 25: [Conversion slope for Flow meter 2]
Line 26: [Conversion offset for Flow meter 2]
Line 27: [Conversion type for Flow meter 2]
Line 28: [Calculated units for Flow meter 2]
Line 29: [Conversion name for Upper Transducer]
Line 30: [Conversion description for Upper Transducer]
Line 31: [Conversion slope for Upper Transducer]
Line 32: [Conversion offset for Upper Transducer]
Line 33: [Conversion type for Upper Transducer]
Line 34: [Calculated units for Upper Transducer]
Line 35: [Conversion name for Middle Transducer]
Line 36: [Conversion description for Middle Transducer]
Line 37: [Conversion slope for Middle Transducer]
Line 38: [Conversion offset for Middle Transducer]
Line 39: [Conversion type for Middle Transducer]
Line 40: [Calculated units for Middle Transducer]
Line 41: [Conversion name for Lower Transducer]
Line 42: [Conversion description for Lower Transducer]
Line 43: [Conversion slope for Lower Transducer]
Line 44: [Conversion offset for Lower Transducer]
Line 45: [Conversion type for Lower Transducer]
Line 46: [Calculated units for Lower Transducer]
Line 47: 'cbCorrectUpper'
Line 48: [True if the upper transducer should be corrected for barometric pressure.]
Line 49: 'cbCorrectMiddle'
Line 50: [True if the middle transducer should be corrected for barometric pressure.]

```

Line 51: 'cbCorrectLower'
Line 52: [True if the lower transducer should be corrected for barometric pressure.]
Line 53: 'Data_logger_ID',
        tab, 'Year',
        tab, 'Julian_Day',
        tab, 'Hour_Minute',
        tab, 'Seconds',
        tab, 'Data_logger_Temperature',
        tab, 'Barometer_mv',
        tab, 'Upper_Transducer_mV',
        tab, 'Middle_Transducer_mV',
        tab, 'Lower_Transducer_mV',
        tab, 'Flow_meter_1_mV',
        tab, 'Flow_meter_2_mV',
        tab, 'Date_As_Number',
        tab, 'Interpreted_Barometer',
        tab, 'Interpreted_Upper_Transducer',
        tab, 'Interpreted_Middle_Transducer',
        tab, 'Interpreted_Lower_Transducer',
        tab, 'Interpreted_Flow_meter_1',
        tab, 'Interpreted_Flow_meter_2',
        tab, 'Barometer_Units',
        tab, 'Upper_Transducer_Units',
        tab, 'Middle_Transducer_Units',
        tab, 'Lower_Transducer_Units',
        tab, 'Flow_meter_1_Units',
        tab, 'Flow_meter_2_Units'

```

Line 54 to end of file: [Data in same order as in line 53. Each datum is separated by a tab character.]

Example

The following is an example of an interpreted data file. Lines 54-56 have been wrapped to multiple lines to show all the data on those lines.

```

Program = Bat3
Program Version = 0.22.0.0
File type = Interpreted data
48
comboBarometerUnits
Millibars
comboFlowUnits
gallons/min
comboTransducerUnits
ft.
CS105_Barometer
VAISALA PTB101B - Campbell Sci - Barometric Sensor SN W2630005
0.184
600
Pressure
Millibars
1_EG&G_FO96107426
EG&G Flow Technology FTO-5NIYW-LHC-5 SN FO96107426
0.0017018
0.014319
Flow rate
gallons/min

```

2_EG&G_FO96107425
 EG&G Flow Technology FTO-1NIYW-LHC-5
 6.6436E-5
 0.0015423
 Flow rate
 gallons/min
 Drk50psia_1379787
 Druck PDCR 1830 - 6 wire - 50 psia SN 139787
 11.581429
 0.227034
 height of water above transducer
 ft.
 Drk100psia_992057
 Druck PDCR 1830 - 6 wire - 100 psia SN 992057
 23.398342
 -0.4132756
 height of water above transducer
 ft.
 Drk100psia_992056
 Druck PDCR 1830 - 6 wire - 100 psia SN 992056
 23.460676
 -0.061752
 height of water above transducer
 ft.
 cbCorrectUpper
 True
 cbCorrectMiddle
 True
 cbCorrectLower
 True

Data_logger_ID	Year	Julian_Day	Hour_Minute	Seconds	Data_logger_Temperature	Barometer_mv	Upper_Transducer_mV	Middle_Transducer_mV	Lower_Transducer_mV	Flow_meter_1_mV	Flow_meter_2_mV	Date_As_Number	Interpreted_Barometer	Interpreted_Upper_Transducer	Interpreted_Middle_Transducer	Interpreted_Lower_Transducer	Interpreted_Flow_meter_1	Interpreted_Flow_meter_2	Barometer_Units	Upper_Transducer_Units	Middle_Transducer_Units	Lower_Transducer_Units	Flow_meter_1_Units	Flow_meter_2_Units				
108	2001	339	1130		1.000000000000000E+0000	2.483300000000000E+0001	2.261700000000000E+0003	2.915600000000000E+0000	1.184400000000000E+0000	1.422300000000000E+0000	0.000000000000000E+0000		0.000000000000000E+0000	3.72304791782406E+0004	1.016152800000000E+0003	-3.14059746643807E-0002	-	6.72553370226438E+0000	-7.18886892264379E-0001	0.000000000000000E+0000	0.000000000000000E+0000	0.000000000000000E+0000	Millibars	ft.	ft.	ft.	gallons/min	gallons/min
108	2001	339	1130		3.100000000000000E+0001	2.489700000000000E+0001	2.261400000000000E+0003	2.915400000000000E+0000	1.183600000000000E+0000	1.421300000000000E+0000	3.333000000000000E-0002		3.333000000000000E-0002	3.72304795254630E+0004	1.016097600000000E+0003	-3.18739222606581E-0002	-	6.74240403766066E+0000	-7.40499230060657E-0001	1.43757209940000E-0002	1.54451431188000E-0003	Millibars	ft.	ft.	ft.	gallons/min	gallons/min	
108	2001	339	1131		1.000000000000000E+0000	2.496600000000000E+0001	2.261700000000000E+0003	2.915500000000000E+0000	1.183400000000000E+0000	1.421300000000000E+0000	0.000000000000000E+0000		0.000000000000000E+0000	3.72304798726851E+0004	1.016152800000000E+0003	-3.25641175643767E-0002	-	6.74893204426438E+0000	-7.42347568264378E-0001	0.000000000000000E+0000	0.000000000000000E+0000	0.000000000000000E+0000	Millibars	ft.	ft.	ft.	gallons/min	gallons/min

Appendix 3 : Conversion Setup File (*.suf)

The conversion **Setup** file is an ASCII text file that describes how the data from each sensor should be converted to meaningful units.

(Lines 4-51 are identical with lines 5-52 of the Interpreted Data File-(*.idf).)

```
Line 1: 'Program = Bat3'  
Line 2: 'Program Version = ' [version]  
Line 3: 'File type = Conversion Setup'  
Line 4: 'comboBarometerUnits'  
Line 5: [Display units for Barometer]  
Line 6: 'comboFlowUnits'  
Line 7: [Display units for flow meters]  
Line 8: 'comboTransducerUnits'  
Line 9: [Display units for pressure transducers];  
Line 10: [Conversion name for Barometer]  
Line 11: [Conversion description for Barometer]  
Line 12: [Conversion slope for Barometer]  
Line 13: [Conversion offset for Barometer]  
Line 14: [Conversion type for Barometer]  
Line 15: [Calculated units for Barometer]  
Line 16: [Conversion name for Flow meter 1]  
Line 17: [Conversion description for Flow meter 1]  
Line 18: [Conversion slope for Flow meter 1]  
Line 19: [Conversion offset for Flow meter 1]  
Line 20: [Conversion type for Flow meter 1]  
Line 21: [Calculated units for Flow meter 1]  
Line 22: [Conversion name for Flow meter 2]  
Line 23: [Conversion description for Flow meter 2]  
Line 24: [Conversion slope for Flow meter 2]  
Line 25: [Conversion offset for Flow meter 2]  
Line 26: [Conversion type for Flow meter 2]  
Line 27: [Calculated units for Flow meter 2]  
Line 28: [Conversion name for Upper Transducer]  
Line 29: [Conversion description for Upper Transducer]  
Line 30: [Conversion slope for Upper Transducer]  
Line 31: [Conversion offset for Upper Transducer]  
Line 32: [Conversion type for Upper Transducer]  
Line 33: [Calculated units for Upper Transducer]  
Line 34: [Conversion name for Middle Transducer]  
Line 35: [Conversion description for Middle Transducer]  
Line 36: [Conversion slope for Middle Transducer]  
Line 37: [Conversion offset for Middle Transducer]  
Line 38: [Conversion type for Middle Transducer]  
Line 39: [Calculated units for Middle Transducer]  
Line 40: [Conversion name for Lower Transducer]  
Line 41: [Conversion description for Lower Transducer]  
Line 42: [Conversion slope for Lower Transducer]  
Line 43: [Conversion offset for Lower Transducer]  
Line 44: [Conversion type for Lower Transducer]  
Line 45: [Calculated units for Lower Transducer]  
Line 46: 'cbCorrectUpper'  
Line 47: [True if the upper transducer should be corrected for barometric pressure.]  
Line 48: 'cbCorrectMiddle'  
Line 49: [True if the middle transducer should be corrected for barometric pressure.]
```

Line 50: 'cbCorrectLower'

Line 51: [True if the lower transducer should be corrected for barometric pressure.]

Example

```
Program = Bat3
Program Version = 0.15.0.0
File type = Conversion Setup
comboBarometerUnits
Millibars
comboFlowUnits
gallons/min
comboTransducerUnits
ft.
CS105_Barometer
VAISALA PTB101B - Campbell Sci - Barometric Sensor SN W2630005
0.184
600
Pressure
Millibars
1_EG&G_FO96107426
EG&G Flow Technology FTO-5NIYW-LHC-5 SN FO96107426
0.0017018
0.014319
Flow rate
gallons/min
2_EG&G_FO96107425
EG&G Flow Technology FTO-1NIYW-LHC-5
6.6436E-5
0.0015423
Flow rate
gallons/min
Drk50psia_1379787
Druck PDCR 1830 - 6 wire - 50 psia SN 139787
11.581429
0.227034
height of water above transducer
ft.
Drk100psia_992057
Druck PDCR 1830 - 6 wire - 100 psia SN 992057
23.398342
-0.4132756
height of water above transducer
ft.
Drk100psia_992056
Druck PDCR 1830 - 6 wire - 100 psia SN 992056
23.460676
-0.061752
height of water above transducer
ft.
cbCorrectUpper
True
cbCorrectMiddle
True
cbCorrectLower
True
```

Appendix 4: Calibration Library File (*.cvi)

The **Calibration Library** file is an ASCII text file is a compilation of calibrations of the various sensors that convert measured responses of the sensors to physically meaningful values.

```
Line 1: 'Program = Bat3'  
Line 2: 'Program Version = ' [version]  
Line 3: 'File type = Conversion'  
Line 4: [Slope], tab, [OffSet], tab, [SensorType], tab, [ConversionName]  
Line 5: [Description]  
Line 6: [Conversion type]  
Line 7: [Units]
```

(Lines 4-7 are repeated for each calibration for a sensor.)

Example

```
Program = Bat3  
Program Version = 0.10.0.0  
File type = Conversion  
0.184 600 0 CS105_Barometer  
VAISALA PTB101B - Campbell Sci - Barometric Sensor SN W2630005  
Pressure  
Millibars  
1.4367 0.14103 0 Drk15psia_1313912  
Druck PDCR 1830 - 6-wire - 15 psia SN 1313912  
Pressure  
Pounds per square inch  
1.4419 -0.023326 0 Drk15psia_1313913  
Druck PDCR 1830 - 6 wire - 15 psia SN 1313913  
Pressure  
Pounds per square inch  
2.32806 -0.215223 2 Drk10psig_1188193  
Druck PDCR 1830 - 6 wire - 10 psig SN 1188193  
height of water above transducer  
ft.  
11.675623 -0.704444 2 Drk50psia_1379785  
Druck PDCR 1830 - 6 wire - 50 psia SN 1379785  
height of water above transducer  
ft.  
11.581429 0.227034 2 Drk50psia_1379787  
Druck PDCR 1830 - 6 wire - 50 psia SN 1379787  
height of water above transducer  
ft.  
23.460676 -0.061752 2 Drk100psia_992056  
Druck PDCR 1830 - 6 wire - 100 psia SN 992056  
height of water above transducer  
ft.  
23.398342 -0.4132756 2 Drk100psia_992057  
Druck PDCR 1830 - 6 wire - 100 psia SN 992057  
height of water above transducer  
ft.  
50.153487 1.197806 2 Drk200psia_1379797  
Druck PDCR 1830 - 6 wire - 200 psia SN 1379797  
height of water above transducer
```

ft.
50.167339 -0.981622 2 Drk200psia_1379799
Druck PDCR 1830 - 6 wire - 200 psia SN 1379799
height of water above transducer
ft.
50.123474 0.449451 2 Drk200psia_1379802
Druck PDCR 1830 - 6 wire - 200 psia SN 1379802
height of water above transducer
ft.
50.135018 -0.945284 2 Drk200psia_1379803
Druck PDCR 1830 - 6 wire - 200 psia SN 1379803
height of water above transducer
ft.
0.0017018 0.014319 1 1_EG&G_FO96107426
EG&G Flow Technology FTO-5NIYW-LHC-5 SN FO96107426
Flow rate
gallons/min
6.6436E-5 0.0015423 1 2_EG&G_FO96107425
EG&G Flow Technology FTO-1NIYW-LHC-5
Flow rate
gallons/min
0.004357 0.0025888 1 A_EG&G_807964
EG&G Flow Technology FT-08NEXW-LEG-5 SN 807964
Flow rate
gallons/min
0.0052381 -0.00010545 1 A_EG&G_8010113
EG&G Flow Technology FT-08NEXW-LEG-5 SN 8010113
Flow rate
gallons/min

Appendix 5: Calibration Files (*.cal)

The **Calibration** file is an ASCII text file that records the data used to calibrate a sensor.

Line 1: Program = Bat3
Line 2: 'Program Version = ' [version]
Line 3: 'File type = Calibration'
Line 4: 'Data type = ', [data type name], tab, [number of data type (Barometer =0, Flow meter1 = 1, ...)]
Line 5: 'Correct for Barometer =', tab, [True or False]
Line 6: 'Depth units = ', [depth unit name], tab, [depth unit number (m=0, ft. = 1)]
Line 7: 'Conversion = ', tab, [Conversion name]
Line 8: [a header line]
Line 9: [a tab-delimited line of data as specified in the header line]

Example

Lines 8 –13 have been wrapped to show all the data on them.

```
Program = Bat3
Program Version = 0.18.0.0
File type = Calibration
Data type = Lower Transducer 5
Correct for Barometer = True
Depth units = ft. 1
Conversion = CS105_Barometer
Date_and_time Date_Time_As_Number mV_reading
    Depth_to_Transducer Depth_to_Water Barometer_mV_reading
Dec 5 2001; 12:05:01.0 3.72305034837962E+0004 1.9836 58.22
    40.41 2.258700000000000E+0003
Dec 5 2001; 13:24:01.0 3.72305583449073E+0004 3.3159 91.49
    42.28 2.251800000000000E+0003
Dec 5 2001; 14:11:31.0 3.72305913310185E+0004 4.8876 127.72
    41.88 2.248600000000000E+0003
Dec 5 2001; 14:51:31.0 3.72306191087963E+0004 6.3742 163.5
    41.91 2.245900000000000E+0003
Dec 5 2001; 15:44:01.0 3.72306555671295E+0004 6.5436 163.5
    37.85 2.245200000000000E+0003
```

Appendix 6: Parameter Value Files (*.pv)

The parameter value file is an ASCII text file that records the data used to calculate model parameters.

If this file is opened using the BAT³ Analyzer, the data in this file after line 45 are not read. The data listed in this file after line 45 are saved to facilitate analysis or display using other software.

N = number of model values

T = number of transducer values

Line 1: Program = Bat3

Line 2: 'Program Version = ' [version]

Line 3: 'File type = Parameter values'

Line 4: 'Model = ' [model version, 0 = Steady state radial flow, 1 = transient radial flow, etc.]

Line 5: 'TSL = [value]

Line 6: 'NP = ' [value]

Line 7: 'INJ = ' [value]

Line 8: 'IOPEN = ' [value]

Line 9: 'HI = ' [value]

Line 10: 'HI Units = ' [value]

Line 11: 'Q = ' [value]

Line 12: 'Q Units = ' [value]

Line 13: 'RINF = ' [value]

Line 14: 'RINF Units = ' [value]

Line 15: 'RS = ' [value]

Line 16: 'RS Units = ' [value]

Line 17: 'RC = ' [value]

Line 18: 'RC Units = ' [value]

Line 19: 'HS = ' [value]

Line 20: 'HS Units = ' [value]

Line 21: 'DLEN = ' [value]

Line 22: 'DLEN Units = ' [value]

Line 23: 'CW = ' [value]

Line 24: 'CW Units = ' [value]

Line 25: 'RHO = ' [value]

Line 26: 'RHO Units = ' [value]

Line 27: 'GRAV = ' [value]

Line 28: 'GRAV Units = ' [value]

Line 29: 'T = ' [value]

Line 30: 'T Units = ' [value]

Line 31: 'ST = ' [value]

Line 32: 'VK = ' [value]

Line 33: 'VK Units = ' [value]

Line 34: 'B = ' [value]

Line 35: 'B Units = ' [value]

Line 36: 'SM = ' [value]

Line 37: 'BE = ' [value]

Line 38: 'BE Units = ' [value]

Line 39: 'Starting Time = ' [value]

Line 40: 'Test Duration = ' [value]

Line 41: 'Log X = ' [True or False]

Line 42: 'Log Y = ' [True or False]

Line 43: 'Plot Drawdown = ' [True or False]

Line 44: 'Data File Name = ' [the fully qualified file name of the data file that is currently open]
Line 45: (blank)
Line 46: 'Model Values'
Line 47: [X coordinate direction caption] tab character [Y coordinate direction caption]
Lines 48 to 48+N-1: [X model value] tab character [Y model value]
Line 48+N: (blank)
Line 48+N+1 to 48+N+T: [X transducer value] tab character [Y transducer value]

Example

In the following example, Line 44 has been wrapped to show all the data on the line.

```
Program = Bat3
Program Version = 0.22.0.0
File type = Parameter values
Model = 0
TSL = 0
NP = 10
INJ = 1
IOPEN = 0
HI = 114.686
HI Units = ft.
Q = 1.23155
Q Units = gallons/min
RINF = 15
RINF Units = ft.
RS = 3
RS Units = in.
RC = 0
RC Units = in.
HS = 0
HS Units = ft.
DLEN = 0
DLEN Units = ft.
CW = 4.6e-10
CW Units = m^2/N
RHO = 1000
RHO Units = kg/m^3
GRAV = 9.80665
GRAV Units = m/sec^2
T = 5.2e-6
T Units = m^2/s
ST = 1e-5
VK = 1e-6
VK Units = m/s
B = 1
B Units = m
SM = 1e-5
BE = 0
BE Units = 1/s
Starting Time = 3.72306458449074E+0004
Test Duration = 15
Log X = False
Log Y = False
Plot Drawdown = False
Data File Name = C:\Program
Files\Borland\Delphi5\Projects\Bat3\tutorial\WMATA_2001_339A.DAT
```

Model Values

Elapsed time (sec)	Head (ft.)
1.000000000000000E+0000	1.46630797647788E+0002
1.25892541179417E+0000	1.46630797647788E+0002
1.58489319246111E+0000	1.46630797647788E+0002
1.99526231496888E+0000	1.46630797647788E+0002
2.51188643150958E+0000	1.46630797647788E+0002
3.16227766016838E+0000	1.46630797647788E+0002
3.98107170553497E+0000	1.46630797647788E+0002
5.01187233627272E+0000	1.46630797647788E+0002
6.30957344480193E+0000	1.46630797647788E+0002
7.94328234724282E+0000	1.46630797647788E+0002
1.000000000000000E+0001	1.46630797647788E+0002
1.25892541179416E+0001	1.46630797647788E+0002
1.58489319246111E+0001	1.46630797647788E+0002
1.99526231496888E+0001	1.46630797647788E+0002
2.51188643150958E+0001	1.46630797647788E+0002
3.16227766016838E+0001	1.46630797647788E+0002
3.98107170553497E+0001	1.46630797647788E+0002
5.01187233627272E+0001	1.46630797647788E+0002
6.30957344480193E+0001	1.46630797647788E+0002
7.94328234724281E+0001	1.46630797647788E+0002
1.000000000000000E+0002	1.46630797647788E+0002
1.25892541179416E+0002	1.46630797647788E+0002
1.58489319246111E+0002	1.46630797647788E+0002
1.99526231496888E+0002	1.46630797647788E+0002
2.51188643150958E+0002	1.46630797647788E+0002
3.16227766016838E+0002	1.46630797647788E+0002
3.98107170553497E+0002	1.46630797647788E+0002
5.01187233627272E+0002	1.46630797647788E+0002
6.30957344480193E+0002	1.46630797647788E+0002
7.94328234724281E+0002	1.46630797647788E+0002
1.000000000000000E+0003	1.46630797647788E+0002

Pressure Transducer Values

Elapsed time (sec)	Head (ft.)
3.00000000977889E+0001	1.14840490280609E+0002
5.99999901372939E+0001	1.14782119042347E+0002
9.00000002933666E+0001	1.14714139233809E+0002
1.19999990332871E+0002	1.14697760394409E+0002
1.50000000488944E+0002	1.14676701886609E+0002
1.79999989899807E+0002	1.14686061223409E+0002
2.10000000055879E+0002	1.41264237901210E+0002
2.39999990095384E+0002	1.43526857572610E+0002
2.70000000251457E+0002	1.44418334402810E+0002
2.9999990290962E+0002	1.44955880156075E+0002
3.30000000447035E+0002	1.45271757773075E+0002
3.5999990486540E+0002	1.45543178540275E+0002
3.90000000013970E+0002	1.45700438927671E+0002
4.19999990053475E+0002	1.45821618810075E+0002
4.50000000209548E+0002	1.45971368198875E+0002
4.79999990249053E+0002	1.46097719245675E+0002
5.10000000405125E+0002	1.46203011784675E+0002
5.39999990444630E+0002	1.46289585650075E+0002
5.6999999972060E+0002	1.46380223071140E+0002
5.99999990011565E+0002	1.46476156273340E+0002

6.30000000167638E+0002	1.46548691133540E+0002
6.59999990207143E+0002	1.46602507320140E+0002
6.90000000363216E+0002	1.21252743597340E+0002
7.19999990402721E+0002	1.19116474972740E+0002
7.49999999930151E+0002	1.18821655863540E+0002
7.79999989969656E+0002	1.18765499842740E+0002
8.10000000125729E+0002	1.18655527635340E+0002
8.39999990165234E+0002	1.18632129293340E+0002
8.70000000321306E+0002	1.18561934267340E+0002
8.99999990360811E+0002	1.18498267247944E+0002

Appendix 7: Theoretical Background for 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. This section is intended to briefly describe the underlying assumptions for estimating hydraulic properties from single-hole hydraulic tests, such as those conducted with the Multifunction BAT³, and the assumptions underlying the hydrogeologic conceptual models used to estimate hydraulic properties in the BAT³ Analyzer. The hydraulic properties that are estimated from the interpretation of the single-hole hydraulic tests will depend on the hydrogeologic conceptual model of the aquifer that is considered. A discussion of the various hydrogeologic conceptual models that are considered as part of the interpretational software in the BAT³ Analyzer is discussed in the sections that follow.

Single-Hole Hydraulic Tests in Fractured Rock

It is widely recognized that fractured rock formations are highly heterogeneous. Bedrock aquifers are not uniformly fractured and the hydraulic properties of fractures can vary over many orders of magnitude. In addition, the hydraulic properties within an individual fracture may vary in space, and intricacies in the connectivity of fractures also contribute to the formation heterogeneity.

Single-hole hydraulic tests cannot identify the spatial distribution of hydraulic properties in heterogeneous formations, because hydraulic responses are measured in the same borehole in which a hydraulic perturbation is introduced. To identify the spatial distribution of heterogeneous hydraulic properties, measurements at multiple locations in the formation must be made (Hsieh and Shapiro, 1996). Nevertheless, single-hole hydraulic tests can be used to identify the hydraulic properties in the vicinity of the borehole, and bulk hydraulic properties of the formation, under simplifying assumptions of homogeneity. It must be remembered, however, that hydraulic properties of bedrock aquifers estimated under the assumption of homogeneity are unlikely to represent the actual flow regime in the formation. The flow regime is likely to be more complex depending on the hydraulic complexity within individual fractures and the connectivity between fractures.

Fluid-injection tests are often conducted over a short duration, and the pressurized-slug tests are conducted by injecting a small volume of water into the test interval. In both instances, only the immediate vicinity of the borehole is likely to be affected by the hydraulic perturbation. In the immediate vicinity of the borehole, a fracture intersecting the borehole could be regarded as being homogeneous. Therefore, interpreting fluid-injection and pressurized-slug tests under the assumption of homogeneous hydraulic properties may be appropriate.

Hydraulic perturbations that are conducted over extended periods of time, such as extended periods of pumping during geochemical sampling, would result in a large volume of the formation being affected by the hydraulic perturbation. With a large volume of the formation being affected, it is more likely that heterogeneous fracture properties and intricacies in the fracture connectivity will affect the hydraulic response in a single-hole test. The assumption of homogeneity may be best applied if only the early-time hydraulic responses from such single-hole tests are used to estimate the hydraulic properties of the test interval.

For hydraulic tests of short duration, or the interpretation of the early-time hydraulic responses in a test interval in the borehole that is isolated by two packers, a two-dimensional, radial flow regime in a homogeneous formation can be used to estimate the hydraulic properties of the test interval. This implies that within an individual fracture, a two-dimensional radial flow regime is established as a result of the hydraulic perturbation in the test interval of the borehole. If multiple fractures intersect the test interval, then within each fracture it is assumed that a two-dimensional radial flow regime is established, and the hydraulic properties that are estimated from the single-hole test are indicative of the aggregated hydraulic properties associated with all of the fractures intersecting the test interval.

Because of the heterogeneous nature of individual fractures due to fracture asperities and variability in the fracture aperture, it is unlikely that the flow regime within an individual fracture intersecting the test interval is truly radially oriented with respect to the borehole. The flow lines within an individual fracture will deflect around constrictions in the fracture aperture. The estimates of the hydraulic properties of the fractures intersecting the test interval, therefore, need to be regarded as bulk hydraulic properties that incorporate the heterogeneity of a nearly radially flow regime within the fracture or fractures intersecting the test interval.

In the immediate vicinity of the borehole it is more likely that conditions nearly resembling radial flow will be met. At greater distances from the borehole, because of intricacies in fracture connectivity and the variability of the hydraulic properties of fractures, it is likely that there will be greater deviation from the assumption of radially oriented flow with respect to the borehole. Therefore, tests of shorter duration or the interpretation of early-time hydraulic responses are likely to be amenable to the assumptions implicit in the interpretation of single-hole hydraulic tests using radial flow and homogeneous hydraulic properties. The interpretation of late-time hydraulic responses from extended periods of pumping can still be conducted using assumptions of homogeneity and two-dimensional radial flow. In the absence of multiple hydraulic measurements at various locations in the formation, the estimated hydraulic properties can provide insight into the ability of the formation to transmit water; however, the assumed flow-regime and its associated hydraulic properties will not provide an accurate interpretation of the fluid pressure responses and flow directions in complexly fractured formations.

The hydraulic properties that are usually estimated from the interpretation of single-hole hydraulic tests are transmissivity and storativity. Transmissivity and storativity are properties of two-dimensional ground-water flow (Bear, 1979). In unconsolidated porous media, transmissivity is equal to the hydraulic conductivity multiplied by the aquifer thickness, and storativity is the specific storage multiplied by the aquifer thickness. Hydraulic conductivity and specific storage are properties of three-dimensional ground-water flow. Investigators may be interested in converting estimates of transmissivity and storativity from the interpretation of single-hole hydraulic tests to hydraulic conductivity and specific storage by dividing by the length of the test interval. Estimates of the hydraulic conductivity and specific storage of a test interval with a discrete number of fractures will not yield an accurate representation of the formation properties. The estimates of the hydraulic conductivity and specific storage will be dependent on the length of the test interval (National Research Council, 1996). For example, if the length of a test interval with a single fracture is increased so that the longer test interval still contains the single fracture, the hydraulic conductivity of the longer test interval is reduced. For this case of a single fracture in test intervals of different lengths, the transmissivity of the test interval remains the same. Consequently, it is

recommended that estimates of hydraulic properties from test intervals with a discrete number of fractures be reported in terms of the transmissivity and storativity of the test interval.

Estimates of the storativity from single-hole hydraulic tests may be subject to great uncertainty. The compressibility of the downhole equipment arising from hydraulic perturbations may mask the storativity of the fractures intersecting the test interval. In general, estimates of the storativity of formations are made with greater confidence from hydraulic responses in boreholes other than the borehole that has been subject to the hydraulic perturbation. Methods of estimating the compressibility of the borehole equipment can be made by conducting fluid-injection tests or pressurized-slug tests in the surface casing of the borehole (see, for example, Neuzil, 1982). The compressibility of the downhole equipment can then be used to estimate the formation storativity from the single-hole hydraulic test in the test interval.

In the following sections, methods are described for estimating the hydraulic properties of the test interval for the various types of single-hole hydraulic tests that can be conducted using the Multifunction BAT³. The methods of interpretation assume homogeneous formation properties and two-dimensional radial flow in the vicinity of the borehole. In addition, the test interval is regarded as being analogous to a confined aquifer, and fluid-withdrawal tests are interpreted under the assumption of a constant pumping rate. Alternative interpretations of the fluid pressure responses and flow rates from the single-hole hydraulic tests conducted with the Multifunction BAT³ can be conducted using other conceptual models of flow in the vicinity of the test interval, for example, linear or spherical flow regimes, as well as predefined spatial distributions of heterogeneous hydraulic properties, and time-varying pumping rates. Such conditions, however, are not currently included in the interpretation capabilities of the BAT³ Analyzer.

Estimation of the hydraulic properties of the test interval using the interpretation capabilities of the BAT³ Analyzer are made using the fluid pressure responses in the test interval. The fluid pressure responses above and below the test interval that are measured with the top- and bottom-zone transducers are not incorporated in the method of estimating the hydraulic properties of the test interval. The responses of the top- and bottom-zone transducers, however, should be referred to in assessing the validity of the assumption of a two-dimensional radial flow in the vicinity of the test interval. Changes in fluid pressure above the top packer and below the bottom packer that are similar in magnitude to the fluid pressure responses in the test interval indicate that the assumption of two-dimensional flow in the vicinity of the test interval is not appropriate.

Fluid-Injection Tests

Fluid-injection tests are conducted by injecting fluid into the test interval and monitoring the change in fluid pressure. In principle, the time-varying flow-rate into the test interval and fluid pressure can be interpreted to estimate the transmissivity and storativity of the fractures intersecting the test interval. The compressibility of the downhole equipment, however, interferes with the estimation of the formation storativity, and interpretation methods that account for a time-varying flow rate would need to be used for this purpose.

In many instances, after several minutes of conducting a fluid-injection test, the rate of fluid injection into the test interval and the fluid pressure in the test interval remain relatively constant. Even though there may be a slight time-varying response to the fluid injection, an estimate of the transmissivity can be made by assuming the flow regime in the fractures intersecting the borehole

are under steady-state conditions (Shapiro and Hsieh, 1998). 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),

$$h_w = H_0 + \left(\frac{Q}{2\pi T} \right) \ln \left(\frac{R}{r_w} \right) \quad (\text{A7.1})$$

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 (A7.1) 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. The implementation of the above equation in the BAT³ Analyzer allows the user to choose a value of T that best reproduces the measured hydraulic head in the test interval during the fluid-injection test. The user must also prescribe the radius of influence, R . 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 3 meters (10 ft) in the interpretation of fluid-injection tests conducted in igneous and metamorphic rock.

Fluid-Withdrawal Tests

Fluid-withdrawal tests conducted as part of geochemical sampling or to ascertain the hydraulic properties of highly transmissive fractures intersecting the test interval can be interpreted with the BAT³ Analyzer using various hydrogeologic conceptual models of the formation. The choice of the method of interpretation will depend on the shape of the time-varying fluid pressure response in the test interval. If the fluid pressure response in the test interval is constant or varies only slightly over the time frame of the test, a steady-state approximation may be used to estimate the transmissivity of the test interval. If, however, there is a time-varying hydraulic response in the test interval, a hydrogeologic model that considers a transient flow regime in the vicinity of the borehole should be considered in estimating the hydraulic properties of the test interval. Under the assumption of transient flow, the fluid pressure responses in the test interval can be interpreted with one of following hydrogeologic models in the BAT³ Analyzer:

1. **Confined aquifer with two-dimensional radial flow to the borehole (Theis, 1935).** The fractures intersecting the borehole in the test interval are assumed to be analogous to confined aquifers.
2. **Semi-confined aquifer with two-dimensional radial flow to the borehole and vertical leakage to the semi-confined aquifer (Hantush, 1967).** The fractures intersecting the borehole

in the test interval are assumed to be analogous to a confined aquifer where there is vertical leakage through a semi-confining unit. The leakage through the semi-confining unit is assumed to be controlled by a time-invariant hydraulic head above the semi-confining unit. In addition, the semi-confining unit is assumed to have no capacity for transient storage of the fluid. Leakage to the fractures intersecting the test interval in the borehole could be as a result of less permeable fractures that are in hydraulic communication with the fractures intersecting the test interval.

3. **Dual-porosity confined aquifer with two-dimensional radial flow to the borehole (Barenblatt and others, 1960).** The fractures intersecting the borehole in the test interval are assumed to be in hydraulic communication with fluid in the primary porosity of the rock or fluid in less permeable fractures that have a different storativity than the transmissive fractures intersecting the test interval.

The shape of the time-varying fluid pressure response may indicate the type of hydrogeologic conceptual model that is appropriate in the interpretation of the hydraulic data and the estimation of the hydraulic properties of the test interval. Figure A7.1 shows the characteristic shape of time-varying fluid pressure responses to pumping for two-dimensional radial flow in a confined aquifer, a semi-confined aquifer with vertical leakage, and a dual porosity aquifer. Other hydrogeologic conceptual models may also be appropriate in the interpretation of the fluid-withdrawal test conducted with the Multifunction BAT³, but they are currently not implemented in the interpretation capabilities of the BAT³ Analyzer.

Steady-State Flow

In some instances, fluid-withdrawal tests may show similar hydraulic responses to those of fluid-injection tests. For example, for a constant pumping rate, a constant hydraulic head in the test interval may be achieved, which is analogous to a steady-state flow regime. Under this condition, equation (A7.1) can be modified to estimate the transmissivity of the test interval from a fluid-withdrawal test,

$$h_w = H_0 - \left(\frac{Q}{2\pi T} \right) \ln \left(\frac{R}{r_w} \right) \quad (\text{A7.2})$$

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 pumping rate, which is assumed to be constant, 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. The implementation of equation (A7.2) in the BAT³ Analyzer allows the user to choose a value of T that best reproduces the measured hydraulic head in the test interval.

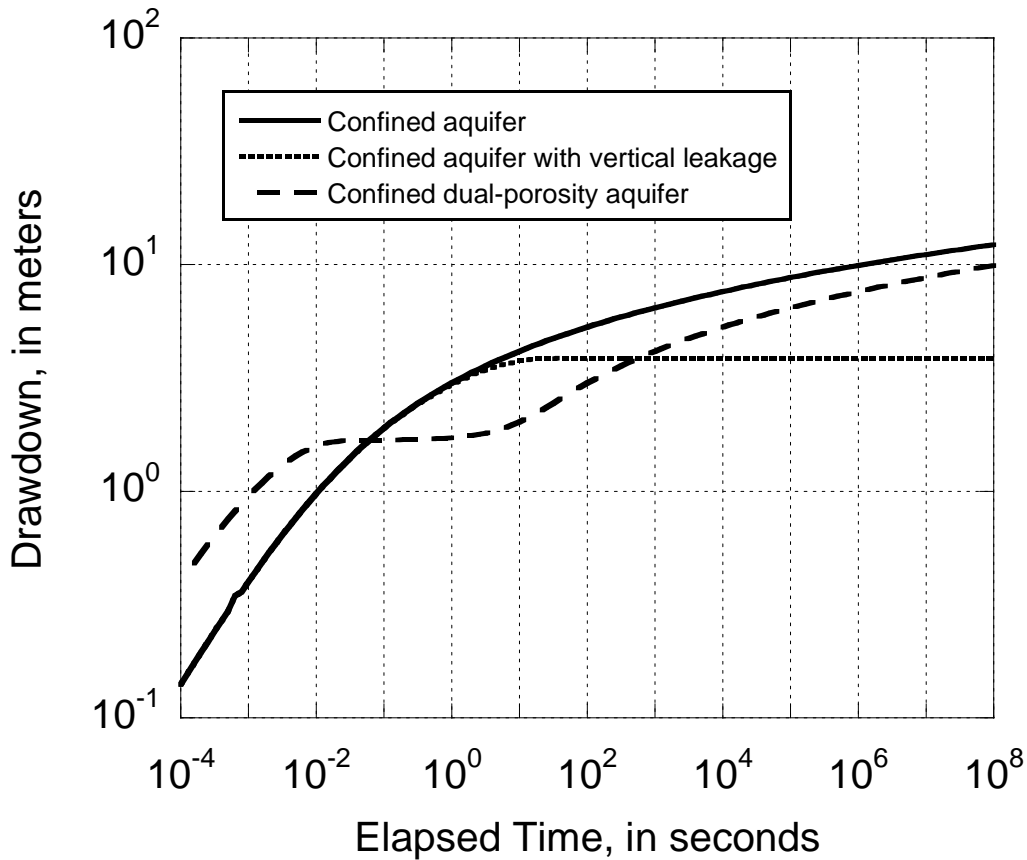


Figure A7.1. Drawdown versus time for various hydrogeologic conceptual models of responses to fluid withdrawals in a pumped interval that is hydraulically isolated by two packers.

For fluid-withdrawal tests, however, a constant hydraulic head in the test interval may be indicative of other hydrogeologic conditions, for example, leakage to the fractures intersecting the test interval. The leakage may be in the form of less permeable fractures acting as a source of water to the fractures intersecting the borehole in the test interval. Other methods of interpreting fluid-withdrawal tests where there is a constant hydraulic head measured in the test interval after some period of pumping are discussed below.

Transient Flow - Confined Aquifer

The transient pressure response in the test interval may be able to be interpreted by assuming that the fractures intersecting the test interval are analogous to a confined aquifer subject to two-dimensional radial flow to the borehole. The partial differential equation describing this condition is

$$S \frac{\partial h}{\partial t} - T \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial h}{\partial r} \right) = 0 \quad (\text{A7.3})$$

where h is the hydraulic head in the formation, which varies as a function of the radial coordinate, r , and time, t , S is the formation storativity, and T is the formation transmissivity. The hydraulic head is assumed to be constant in the formation and equal to H_0 at the start of pumping,

$$h(r, t = 0) = H_0 \quad (\text{A7.4})$$

At the borehole, the relation between the pumping rate and the hydraulic head is

$$Q = 2\pi r_w T \left. \frac{\partial h}{\partial r} \right|_{r=r_w} \quad (\text{A7.5})$$

Also, the hydraulic head far from the borehole is assumed to be unaffected by pumping.

$$h(r \rightarrow \infty, t) = H_0 \quad (\text{A7.6})$$

The solution to equations (A7.3)-(A7.6) was first given by Theis (1935), and this solution is implemented in the interpretation capabilities of the BAT³ Analyzer. The implementation in the BAT³ Analyzer allows the user to choose values of T and S that best reproduce the measured hydraulic head in the test interval during the period of pumping. Under steady-state conditions, the solution reduces to the Thiem equation (Bear, 1979).

Transient Flow - Semi-Confined Aquifer with Leakage

Pumping at a constant rate may result in a transient fluid pressure response in the test interval that resembles responses in a semi-confined aquifer subject to leakage (see fig. A7.1). The test interval is not assumed to have similar physical characteristics as the hydrogeologic model originally proposed by Hantush (1967). Fractures intersecting the borehole in the test interval may be in hydraulic communication with the less permeable fractures that behave analogously to a semi-confining unit, and these less permeable fractures may be in contact with more transmissive fractures that act as a source of water when pumping the test interval.

The partial differential equation describing two-dimensional radial flow to a borehole with vertical leakage from a semi-confining unit is (Hantush, 1967)

$$S \frac{\partial h}{\partial t} - T \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial h}{\partial r} \right) = \frac{\kappa}{b} (H_0 - h) \quad (\text{A7.7})$$

where h is the hydraulic head in the formation, which varies as a function of the radial coordinate, r , and time, t , S is the formation storativity, and T is the formation transmissivity, κ is the vertical hydraulic conductivity of the semi-confining unit, b is the thickness of the semi-confining unit, and H_0 is the hydraulic head above the semi-confining unit, which is assumed to be constant. The term on the right-hand side of equation (A7.7) represents the vertical leakage to the fractures in the test interval. Equation (A7.7) is also subject to the initial and boundary conditions given by equations (A7.4), (A7.5) and (A7.6).

The solution to equations (A7.4)-(A7.7) was given by Hantush (1967). The implementation of this solution in the BAT³ Analyzer allows the user to choose the values of T , S , κ , and b that best reproduce the measured hydraulic head in the test interval during the period of pumping. Although, κ and b can be specified separately in the BAT³ Analyzer, only the ratio, κ/b will affect the solution for the hydraulic head in the test interval.

Transient Flow - Dual-Porosity Aquifer

Pumping at a constant rate may result in a transient fluid pressure response in the test interval that resembles responses in a dual-porosity aquifer (see fig. A7.1). Under this hydrogeologic conceptual model, the fractures intersecting the borehole in the test interval are assumed to be in hydraulic communication with fluid in a characteristically different void space in the rock, for example, the primary porosity of the rock, or less permeable fractures that are pervasive in the formation. This other void space will be referred to as the matrix porosity. The hydraulic communication between the highly transmissive fractures and the matrix porosity is assumed to be controlled by the release of fluid from compressive storage; the transmissivity of the matrix porosity is assumed to be negligible.

The equations describing two-dimensional radial flow to the borehole in the fracture porosity of a dual-porosity aquifer is (Barenblatt and others, 1960)

$$S \frac{\partial h}{\partial t} - T \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial h}{\partial r} \right) = \beta (h_m - h) \quad (\text{A7.8})$$

where h is the hydraulic head in the fractures, which varies as a function of the radial coordinate, r , and time, t , S is the fracture storativity, T is the fracture transmissivity, h_m is the hydraulic head in the matrix porosity, and β is the rate constant for fluid exchange between fractures and the matrix porosity; β has units of inverse time. The term on the right-hand side of equation (A7.8) represents the rate of fluid exchange between fractures and the matrix porosity. If the hydraulic head in the matrix porosity, h_m , is greater than the hydraulic head in the fracture porosity, h , at a given point, then there is fluid exchange from the matrix porosity to the fracture porosity.

The equation describing ground-water flow in the matrix porosity is

$$S_m \frac{\partial h_m}{\partial t} = -\beta (h_m - h) \quad (\text{A7.9})$$

where S_m is the storativity of the matrix porosity. The term on the right-hand side of equation (A7.9) is the fluid exchange from the matrix porosity to the fractures; this term is the same relation as that given on the right-hand side of equation (A7.8), but with the opposite sign. This means that the rate at which water enters the fracture porosity is equal to the rate at which water leaves the matrix porosity. Additional information about the assumptions inherent in these equations is given in Bear (1993).

Equations (A7.8) and (A7.9) are subject to the initial conditions,

$$h(r, t = 0) = H_0 \quad (\text{A7.10})$$

$$h_m(r, t = 0) = H_0 \quad (\text{A7.11})$$

and the boundary conditions,

$$Q = 2\pi r_w T \left. \frac{\partial h}{\partial r} \right|_{r=r_w} \quad (\text{A7.12})$$

$$h(r \rightarrow \infty, t) = H_0 \quad (\text{A7.13})$$

where H_0 is the hydraulic head in the test interval at the start of the test, and Q is the pumping rate, which is assumed to be constant. Equations (A7.10) and (A7.11) state that the hydraulic head in both the fracture and matrix porosity are equal to H_0 at the start of the test. Equation (A7.13) states that there is no affect of pumping at large distances from the borehole, and equation (A7.12) defines the relation between the pumping rate and the hydraulic head at the borehole.

The solution to equations (A7.8)-(A7.13) was first derived by Barenblatt and others (1960). The implementation of this solution in the BAT³ Analyzer allows the user to choose values of T , S , S_m and β that best reproduce the measured hydraulic head in the test interval during the period of pumping.

Pressurized-Slug Tests

Pressurized-slug tests conducted with the Multifunction BAT³ can also be interpreted using the BAT³ Analyzer. Under the assumption that the test interval in the borehole behaves analogously to a confined aquifer subject to two-dimensional radial flow in the vicinity of the borehole, equation (A7.3) describes the ground-water flow in the vicinity of the borehole during the test (Bredehoeft and Papadopoulos, 1980). The hydraulic head in the formation at the start of the test is assumed to equal to H_0 , with the exception of the hydraulic perturbation imposed by pressurizing the test interval at the start of the test. These conditions are defined by

$$h(r > r_w, t = 0) = H_0 \quad (\text{A7.14})$$

$$h(r = r_w, t = 0) = H_1 \quad (\text{A7.15})$$

where H_1 is the hydraulic head in the test interval that is induced by injecting a small volume of fluid into the test interval. In addition, as given in equation (A7.6), the perturbation at the borehole in the test interval is assumed to have no affect on the hydraulic head at large distances from the borehole.

For the pressurized-slug test, the relation between the flow out of the borehole from the test interval and the hydraulic head in the borehole is given by (Bredehoeft and Papadopoulos, 1980)

$$2\pi r_w T \left. \frac{\partial h}{\partial r} \right|_{r=r_w} - V_w C_w \rho_w g \left. \frac{\partial h}{\partial t} \right|_{r=r_w} = 0 \quad (\text{A7.16})$$

where V_w is the volume of water in the test interval, C_w is the compressibility of the water in the test interval, ρ_w is the density of water, and g is the coefficient of gravitational acceleration. The first term on the left-hand side of equation (A7.16) defines the flow out of the borehole, and the second term on the left-hand side of equation (A7.16) defines the storage of water in the borehole due to the compressibility of the water in the test interval. Neuzil (1982) noted that the compressibility of the downhole equipment may affect the measured hydraulic head in the test interval. He suggested a means of estimating the compressibility of the borehole equipment to be used in place of the compressibility of the water in the above equation.

The solution to equations (A7.3), (A7.6), and (A7.14)-(A7.16) is given in Bredehoeft and Papadopoulos (1980). The implementation of this solution in the BAT³ Analyzer allows the user to choose values of T and S that best reproduce the measured hydraulic head in the test interval during the time that the pressurized-slug test is conducted. The user must also select the values of the volume of water in the test interval, V_w , and the compressibility of water, C_w . These values may be adjusted to account for the compressibility of the downhole equipment as discussed by Neuzil (1982).

Hydraulic Tests with a Free-Water Surface

The downhole components of the Multifunction BAT³ can be operated with only one of the packers being inflated during testing. Under such conditions, the borehole will be divided into two intervals, above and below the inflated packer. If the top packer is inflated, hydraulic tests are conducted below the top packer in a pressurized fluid-filled section of the borehole (from the bottom of the top packer to the bottom of the borehole). For such tests, the boundary conditions applied in the hydrogeologic conceptual models discussed in the previous sections are appropriate in the interpretation of the hydraulic tests.

If the Multifunction BAT³ is operated where only the bottom packer is inflated, then hydraulic testing is conducted above the bottom packer in a borehole with a free-water surface. Under such conditions, the boundary condition applied at the borehole to interpret the transient fluid pressure responses during fluid-withdrawal testing and slug testing need to be modified to account for the free-water surface in the borehole.

Fluid-Withdrawal Tests

For the interpretation of transient flow due to pumping in a confined aquifer, semi-confined aquifer with leakage, and a dual-porosity aquifer, the boundary condition at the borehole is (Papadopoulos and Cooper, 1967)

$$Q = 2\pi r_w T \left. \frac{\partial h}{\partial r} \right|_{r=r_w} - \pi r_c^2 \left. \frac{\partial h}{\partial t} \right|_{r=r_w} \quad (\text{A7.17})$$

where r_c is the radius of the borehole or casing at the free-water surface, Q is the pumping rate, T is the transmissivity, r_w is the radius of the borehole in the test interval, and h is the hydraulic head, which is a function of the radial coordinate, r , and time, t . Equation (A7.17) states that the pumping rate is composed of two components. The first term on the right-hand side of (A7.17) is the contribution to the pumping rate from water entering the borehole from the formation. The second term on the right-hand side of (A7.17) is the contribution to the pumping rate from the water in the borehole. The BAT³ Analyzer implements equation (A7.17) in the solutions for transient fluid pressure responses due to pumping in a test interval with a free-water surface.

The BAT³ Analyzer can implement equation (A7.17) in the interpretation of transient fluid pressure responses due to pumping in a confined aquifer, a semi-confined aquifer, and a dual-porosity aquifer. Figure A7.2 shows characteristic time-varying fluid pressure responses for pumping in a borehole with a free-water surface. In general, for pumping in a borehole with a free-water surface, the fluid pressure response at the onset of pumping will exhibit a unit slope on a plot of the logarithm of the drawdown versus the logarithm of the elapsed time from the start of pumping; drawdown is the change in the water level in the borehole from the initial water level in the borehole.

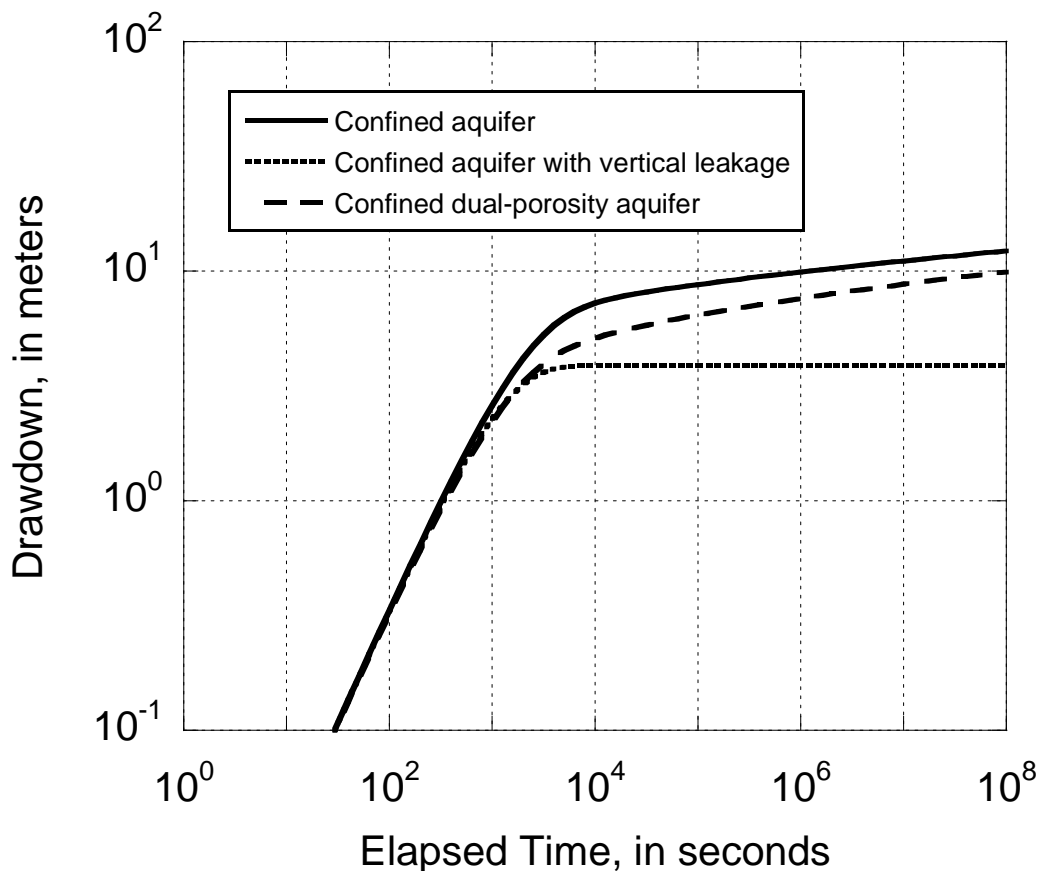


Figure A7.2. Drawdown versus time for various hydrogeologic conceptual models of responses to fluid withdrawals in a pumped interval with a free-water surface.

Slug Tests

A slug test can also be conducted in a borehole with a free-water surface (Cooper and others, 1967). In place of equation (A7.17), the following boundary condition is used to describe the movement of water between the borehole and the formation,

$$0 = 2\pi r_w T \left. \frac{\partial h}{\partial r} \right|_{r=r_w} - \pi r_c^2 \left. \frac{\partial h}{\partial t} \right|_{r=r_w} \quad (\text{A7.18})$$

where r_c is the radius of the borehole or casing at the free-water surface, T is the transmissivity, r_w is the radius of the borehole in the test interval, and h is the hydraulic head, which is a function of the radial coordinate, r , and time, t . Equation (A7.18) states that the flow from the formation (the first term on the right-hand-side of the above equation) is equal to the change in the height of the water in the borehole (the second term on the right-hand side of the above equation); the change in the height of water in the borehole is dependent on the radius of the borehole at the free-water surface.

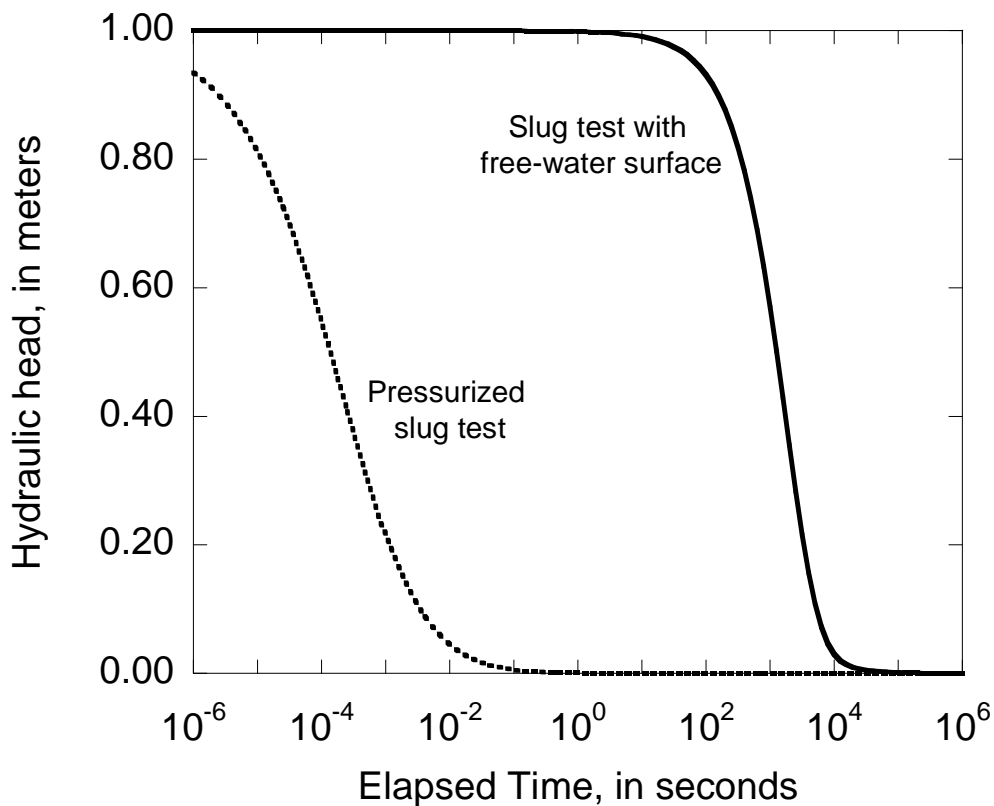


Figure A7.3. Responses for a pressurized slug test and a slug test subject to a free-water surface.

The BAT³ Analyzer can implement equation (A7.18) in the interpretation of transient fluid pressure responses resulting from slug tests conducted in a confined aquifer, where the borehole has a free-water surface. Figure A7.3 compares the hydraulic response associated with a pressurized-slug test and a slug test conducted in a borehole with a free-water surface. The hydraulic perturbation imposed in a pressurized borehole dissipates much more quickly than that in a borehole with a free-water surface. The measured transient hydraulic response in a pressurized-slug test is dependent on the compressibility of the fluid, which is small compared to the physical dimensions of the borehole that control the fluid storage in the borehole and the rate of change in the hydraulic head in the borehole.