# Methods of Conducting Air-Pressurized Slug Tests and Computation of Type Curves for Estimating Transmissivity and Storativity

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## CONTENTS

## ILLUSTRATIONS

## TABLES



## CONVERSION FACTORS

| Multiply | By | To obtain |
|---|---|---|
| meter (m) | 39.37 | inches (in) |
| meter (m) | 3.281 | feet (ft) |
| meters squared per second ($m^2/s$) | $9.3 \times 10^5$ | feet squared per day ($ft^2/d$) |
| kilopascal (kPa) | 0.1450 | pound per square inch (psi) |

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# METHODS OF CONDUCTING AIR-PRESSURIZED SLUG TESTS AND COMPUTATION OF TYPE CURVES FOR ESTIMATING TRANSMISSIVITY AND STORATIVITY

Earl A. Greene and Allen M. Shapiro


## ABSTRACT

Air-pressurized slug tests offer an efficient means of estimating the transmissivity (T) and storativity (S) of aquifers. Air-pressurized slug tests are conducted by pressurizing the air in the casing above the column of water in a well, monitoring the declining water level and then releasing the air pressure and monitoring the rising water level. The equipment needed to conduct an air-pressurized slug test is easily constructed and assembled at the top of the well. The only equipment in contact with the water is a down-hole sensor to monitor water levels. During the pressurized part of the test, small changes in the applied air pressure result in water-level fluctuations, making it difficult to estimate T and S from the declining water-level data. However, if the applied air pressure is maintained until a new equilibrium-water level is achieved and then the air pressure in the well is released instantaneously, the slug test solution of Cooper and others (1967) can be used to estimate T and S from the rising water-level data. In low-permeability formations, it may take an extended period of time to achieve the new equilibrium-water level for the applied air pressure. The total time to conduct the test can be reduced, however, if the pressurized part of the test is terminated prior to achieving the new equilibrium-water level. This is referred to as a prematurely terminated air-pressurized slug test. Type curves generated from the solution of Shapiro and Greene (1995) can be used to estimate T and S from the rising water-level data from prematurely terminated air-pressurized slug tests. The Fortran code AIRSLUG, included in this document, is used to generate the type curves from the solution of Shapiro and Greene (1995). A detailed discussion of the equipment and procedures for conducting air-pressurized slug tests is presented along with discussions of data preparation, use of the Fortran code AIRSLUG, and method of matching the data and the type curves to estimate T and S. Field examples are presented to demonstrate the applicability of air-pressurized slug tests in estimating T and S.


## INTRODUCTION

Although slug tests hydraulically stress a limited volume of the geologic material surrounding a well, they offer a relatively inexpensive means of estimating transmissivity and storativity. The common approach to conducting a slug test involves monitoring the time-varying water level in a well after a volume or "slug" of water is displaced, removed or injected (Figure 1a). Cooper and others (1967) developed a closed-form solution to the equations describing fluid mass conservation in the well and the formation, and presented the results for the time-varying water level as a series of type curves. The type curves depend on dimensionless parameters which are defined in terms of the formation properties and the well geometry. By comparing the measured time-dependent water level with the type curves, the transmissivity and storativity can be estimated.

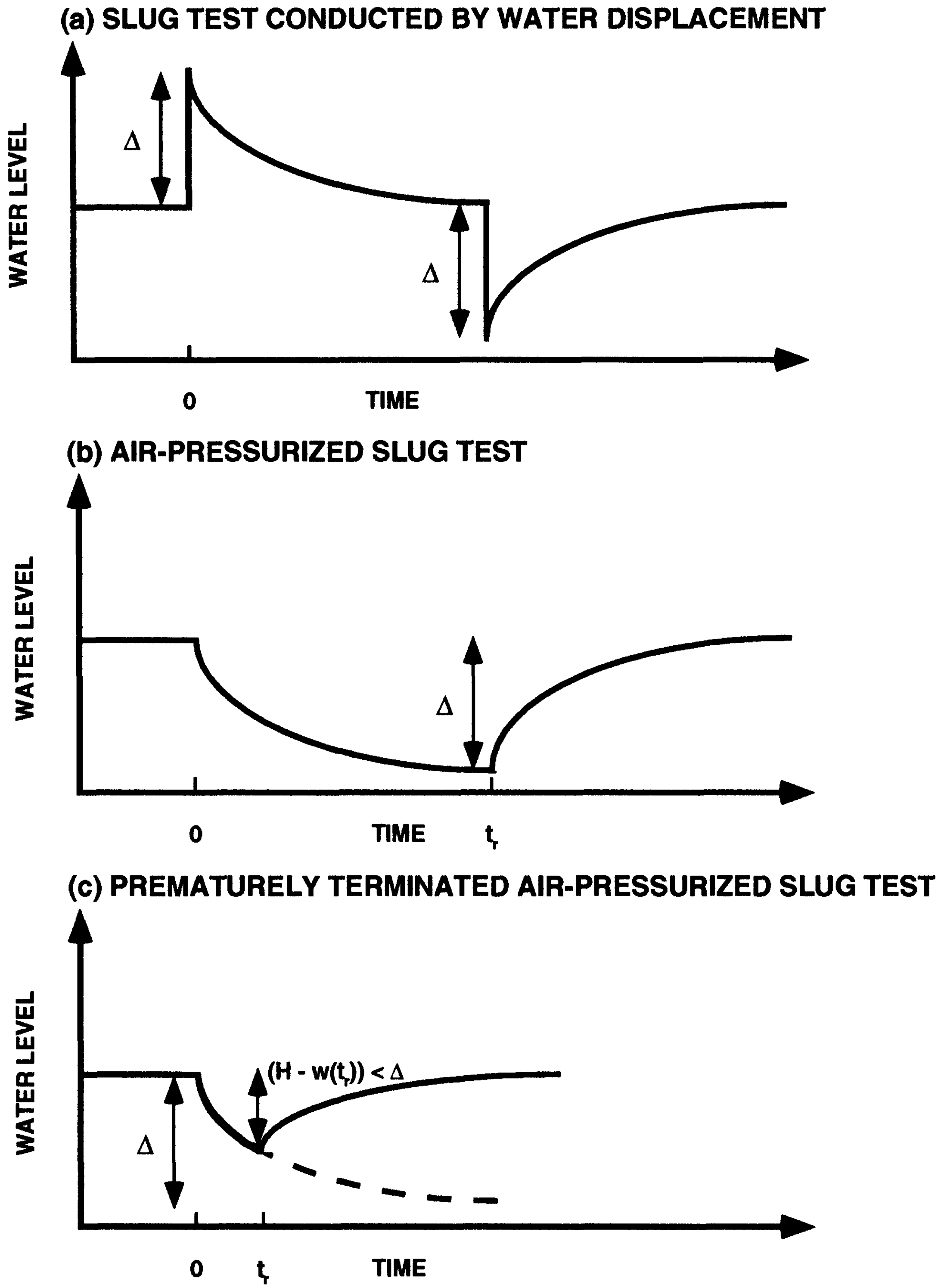


**Figure 1.** Schematic illustrating time-varying water level during (a) slug test conducted by water displacement, (b) air-pressurized slug test, and (c) prematurely terminated air-pressurized slug test, where Δ is the maximum change in water level due to water displacement or an applied air pressure, $t_r$ is the time at which the pressurized part of the air-pressurized slug test is terminated, H is the initial water level at time t = 0, and $w(t_r)$ is the water level at time $t = t_r$.

In many instances, it is impractical to conduct slug tests by adding or removing a column of water from a well (McLane and others, 1991). At sites having contaminated formation waters, removing a column of water poses health concerns because of treating or disposing of contaminated water and cleaning the equipment in contact with the water. Adding a column of water may also be a concern in situations where water chemistry is a consideration, especially in low-permeability formations where foreign water may reside in the vicinity of a monitoring well for an extended period of time. Also, the equipment needed to add or remove a column of water becomes cumbersome in large-diameter wells, or in wells having water levels at significant depths below land surface.

Air-pressurized slug tests offer a means of estimating transmissivity and storativity without directly removing formation water or injecting foreign water into the formation; only a water-level sensor, such as a pressure transducer is required to be in contact with the water in the well (Leap, 1984). The remaining equipment needed to conduct the air-pressurized slug test is assembled at the top of the well casing.

An air-pressurized slug test, as described by Leap (1984), is conducted by applying a constant pressure to the air column in the well at time $t = 0$ and monitoring the declining water level until a new equilibrium-water level is achieved (Figure 1b). The pressure above the water column is then released at time $t = t_r$ and the water level is monitored as it rises to the original static level. If the air column is pressurized instantaneously and held at a constant value, the declining water level during the pressurized part of the test can be analyzed using the slug-test solution of Cooper and others (1967). However, it is difficult to pressurize the air column in the well instantaneously and maintain a constant air pressure as the water level declines. Consequently, the declining water level exhibits fluctuations and estimating formation properties from the type curves of Cooper and others (1967) is problematic.

If the pressurized part of the test is maintained until the new equilibrium-water level is achieved, the rising water level during the recovery part of the test also can be analyzed using the solution of Cooper and others (1967). However, in low-permeability formations an extended period of time is required to achieve the new equilibrium-water level after pressurizing the air column in the well casing. If the pressurized part of the test is terminated prior to achieving the new equilibrium-water level, the type curves from Cooper and others (1967) cannot be used to estimate the formation properties.

Shapiro and Greene (1995) developed a method of analyzing the rising water level (recovery) of air-pressurized slug tests, where the pressurized part of the test is terminated (at time $t = t_r$) prior to achieving the new equilibrium-water level (Figure 1c). This is referred to as a prematurely terminated air-pressurized slug test. A closed form solution to the boundary-value problem for the declining and rising water level during an air-pressurized slug test was developed by Shapiro and Greene (1995) and the results were presented as a series of type curves which are compared with the time-dependent rising water level to estimate the transmissivity and storativity.

When the pressurized part of the test is terminated prior to achieving the new equilibrium-water level, the time needed to conduct an air-pressurized slug tests is reduced significantly, especially in low-permeability formations. Terminating the pressurized part of the test prior to achieving the new equilibrium-water level does not reduce the time needed for the water level to recover to its initial level (Figure 1). However, it significantly can reduce the time needed before initiating the recovery part of the test (Shapiro and Greene, 1995).

The purpose of this report is to present a detailed discussion of the equipment and procedures for conducting air-pressurized slug tests. In addition, this report describes the use of the Fortran code AIRSLUG to generate the type curves needed in estimating transmissivity and storativity from the rising water-level data of a prematurely terminated air-pressurized slug test. This report also presents field examples where air-pressurized slug tests have been conducted and interpreted.

# AIR-PRESSURIZED SLUG TEST

Air pressurized slug tests are conducted by pressurizing the air in the casing above the column of water in a well to depress the water level in the casing to a desired point and then instantly releasing the applied air pressure to initiate recovery. The rising water level during the recovery part of the test is monitored and compared to type curves to estimate transmissivity and storativity.

## Equipment

Figure 2 shows the equipment used to conduct air-pressurized slug tests; a photograph of this equipment at a well site is shown in figure 3. The components of the equipment are: (1) a well-head apparatus; (2) pressure transducers and seals; (3) and an air-delivery system to pressurize the column of air in the well.

### Well-head Apparatus

The main functions of the well-head apparatus are to allow the controlled entry of pressurized air into the well casing, provide access to monitor air pressure and water level, and instantaneously release the air pressure in the well to initiate water-level recovery. When connecting the well-head apparatus to the casing it is important that a pressure-tight seal is made so that there is no leakage of air. One method of achieving this seal is to weld or glue a threaded coupling to the well casing, and then thread the well-head apparatus to the coupling (figure 2). McLane and others (1991) show an example of a well-head apparatus built to the same pipe diameter as the well casing where a rubber sleeve is sealed to the casing with hose clamps. This technique works well when slug tests are conducted in small diameter wells.

A quick-release valve is needed to release the air pressure in the casing rapidly to initiate the recovery part of the test. McLane and others (1991) stress that the opening of the quick-release valve should be approximately the same diameter as the well-head apparatus to return the air pressure in the casing to atmospheric pressure instantly. A 10.2-cm-diameter (4-inch) ball valve was used in the well-head apparatus shown in figure 3 because it is approximately the same diameter as the well casing.

Installing an access port in the well-head apparatus, though not essential, is useful in obtaining manual water-level measurements to determine the static water level before the test, or checking the pressure transducer during the recovery part of the test. The access port for manual measurements only can be used before the air column is pressurized and during the recovery part of the test.

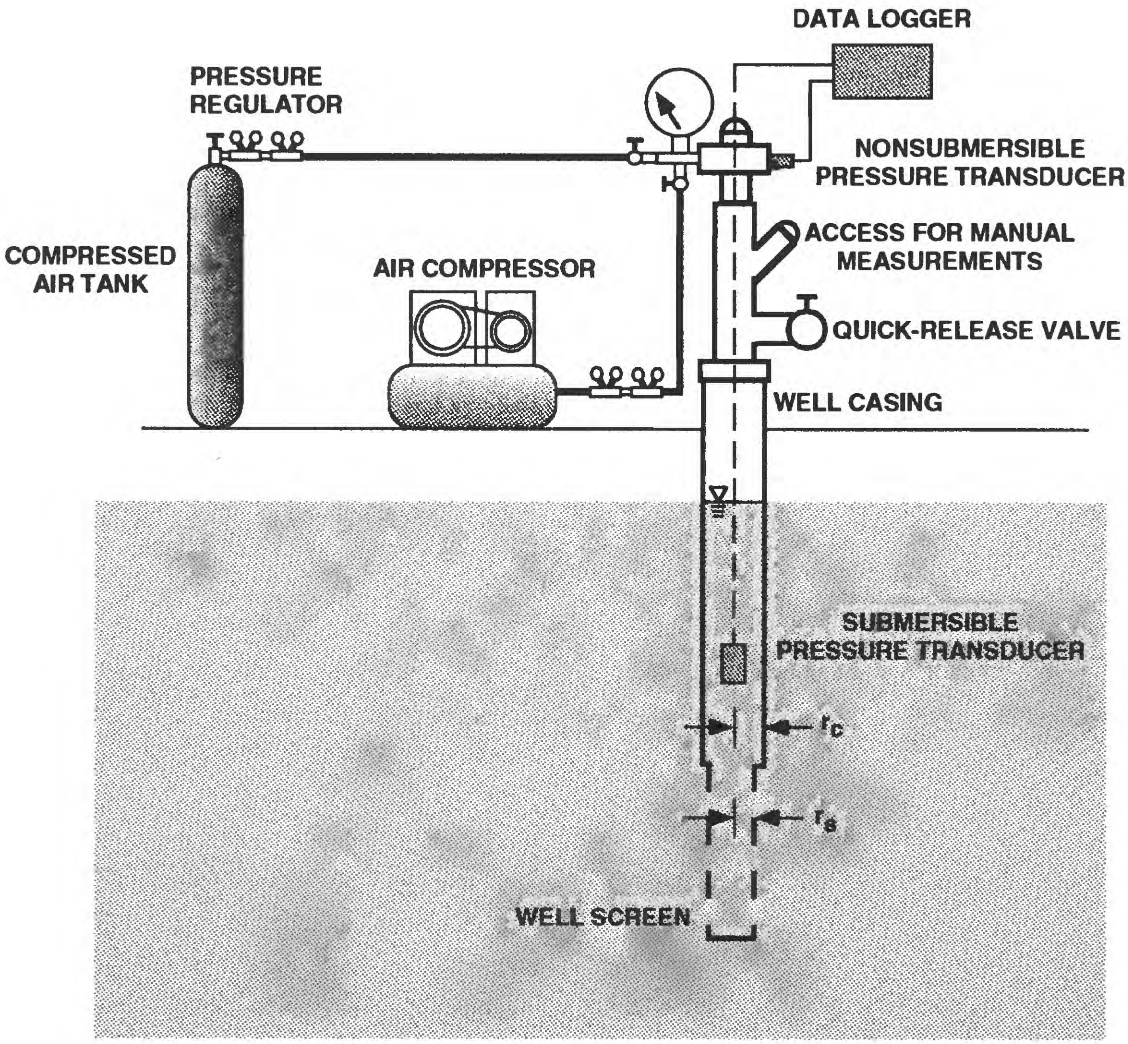


**Figure 2.** Diagram of equipment used to conduct air-pressurized slug tests.

**Figure 3.** Photograph of well-head apparatus and air-delivery system used to conduct air pressurized slug tests. In this design a bottle of nitrogen gas is used to pressurize the column of air in the casing; an air compressor also could have been used to pressurize the well.

## Pressure Transducers and Seals

A submersible pressure transducer is set below the water level to measure water-level response to changes in air pressure (figure 2). Air-tight pressure seals are used to secure the transducer cable to the well-head apparatus. One method of constructing the air-tight seals is shown in figure 4. The pressure seals consist of a thick 1.27-cm-thick (0.5-inch) rubber gasket, two 0.95-cm-thick (0.375-inch) steel plates, and a 5.08-cm-diameter (2-inch) pipe cap with a hole, slightly larger than the size of the transducer cable, drilled in the center. The rubber gasket is sliced from the center to the edge with a thin slot. The steel plates have slots the size of the transducer cable machined from the edge to the center. The transducer cable is then passed through the cap and the rubber gasket. The steel plates are placed above and below the rubber gasket, with the slots rotated so they are offset. Tightening the cap on the pipe (or coupling) compresses the rubber gasket and forms an air-tight seal around the transducer cable.

A second nonsubmersible pressure transducer is used to monitor the air pressure in the casing during the pressurized part of the test. This transducer is connected to the well-head apparatus using threaded pressure fittings. Although it is not necessary to interpret the variation in the air pressure when estimating formation properties, it is important to monitor the air pressure in the casing to verify that a constant air pressure has been applied to the well for a sufficient period of time. The interpretation of the air-pressurized slug test and the use of the type curves discussed in this report are based on the assumption of a constant air pressure acting on the column of water during the pressurized part of the test.

A data logger is used to monitor signals from the pressure transducers at prescribed intervals. The data logger uses internal programs to process data, and stores the processed results for retrieval at a later date. Because the water level and air pressure can not be measured manually during the pressurized part of the test, pressure transducers and a data logger are essential for the successful interpretation of air-pressurized slug tests.

## Air-Delivery System

The key to the air-delivery system for conducting air-pressurized slug tests is to approximate an instantaneously applied constant air pressure. The column of air in the well casing can be pressurized with tanks of compressed air (for example, nitrogen gas) or a portable air compressor (figure 2). In 5.08-cm-diameter (2-inch) wells with a shallow depth to water, only a small volume of air is needed to conduct the test, therefore an air tank will suffice. In large diameter wells or wells having an extensive depth to water, an air compressor can be used for the initial delivery of a large volume of air to raise the pressure to the desired level, and then a tank of compressed air can be used to maintain the pressure for the remainder of the test. In low-permeability formations, a continual source of air pressure may be needed for many hours as the water level in the well drops. One technique to handle this problem is to have multiple air tanks hooked to a pressure regulator to maintain the desired air pressure. Because of the high pressure in compressed-air tanks, up to 20,685 kilopascal (kPa), or equivalently, 3,000 pounds per square inch, (psi), a 2- or 4-stage pressure regulator is needed to reduce the tank pressure to the desired air pressure in the casing.

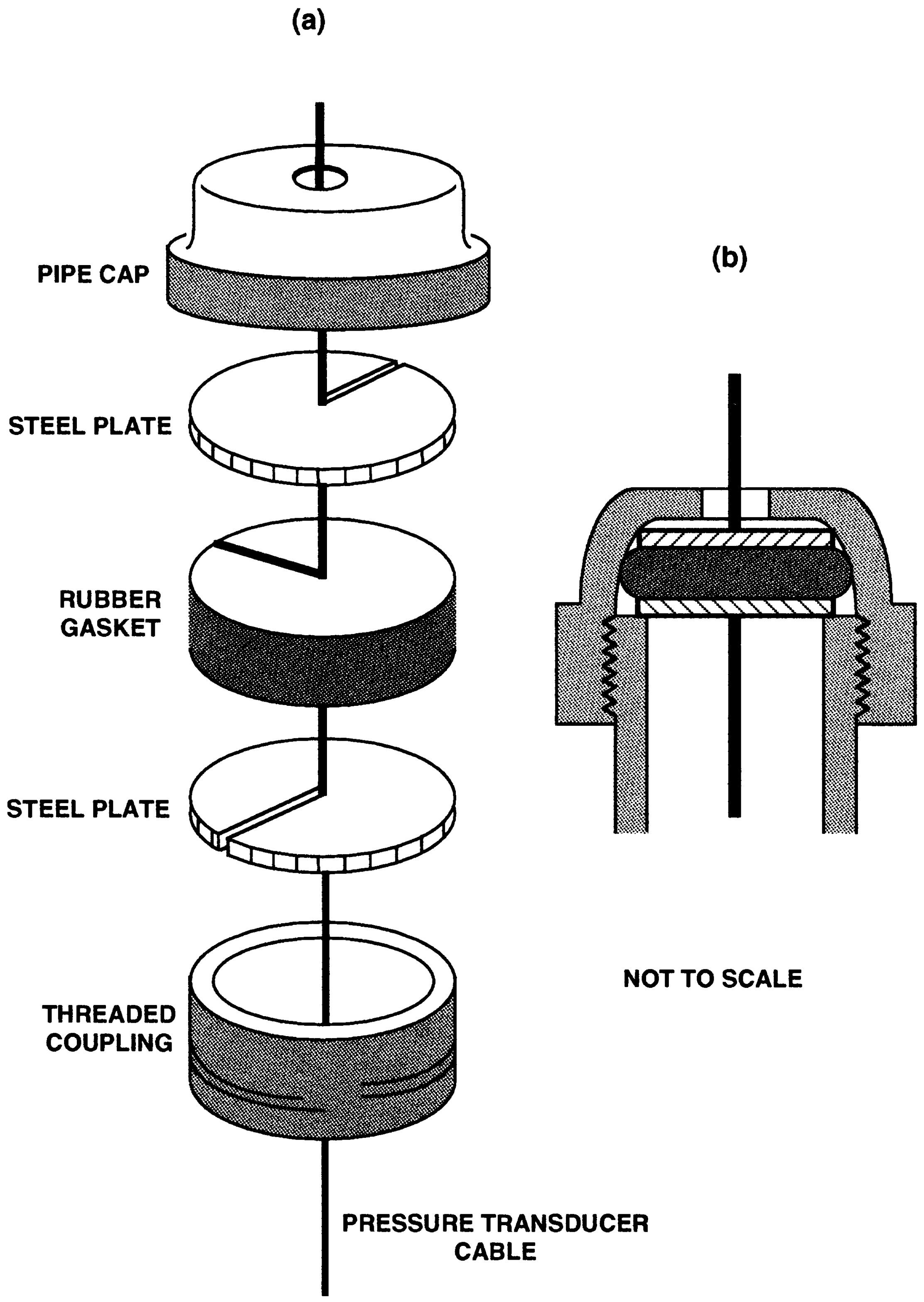


**Figure 4.** Diagram of pressure seals around a pressure transducer cable, (a) exploded view, (b) assembled view.

## Procedure

In order to conduct an air-pressurized slug test, the well casing must be competent to withstand the applied air pressure and have no holes or cracks in the casing or joints. In addition, the well construction information must be known; this includes the radius of the casing, $r_c$ , radius of the well screen or open interval, $r_s$, depth to the static water level, $L_w$ , and depth to the top of the well screen, $L_s$ (figure 5). This information is needed to determine the maximum air pressure that can be applied in the casing and the placement of the submersible pressure transducer that monitors the water level in the well during the pressurized and recovery parts of the test. An outline of the procedure used in conducting and interpreting air-pressurized slug tests is shown in figure 6 and a discussion of the steps shown in figure 6 is presented in the following text.

During the air-pressurized slug test, the water level cannot be forced below the top of the well screen or open interval of the well. Such conditions would force air into the formation and the rising water level would be affected by air blockage in the formation, which is not considered in the interpretation discussed in this report. Therefore, the maximum water-level change during the pressurized part of the test cannot exceed $\Delta_{max} = L_s - L_w$ (figure 5). Thus, the maximum air pressure, $p_{max}$, that can be applied in the casing during the air-pressurized slug test can be calculated as:

$$p_{max} = \frac{L_s - L_w}{0.1020 \frac{m}{kPa}} \qquad \text{or} \qquad p_{max} = \frac{L_s - L_w}{2.3067 \frac{ft}{psi}}$$

where $L_s$ and $L_w$ are measured in units of meters or feet and the maximum applied air pressure is given in units of kPa or psi. In practice, the applied air pressure, $p_a$, should be less than $p_{max}$ so that any surges in the air pressure do not force the water level below the top of the well screen. Consequently, with an applied air pressure, $p_a < p_{max}$, the maximum water-level change associated with the applied air pressure is

$$\Delta = 0.1020 \frac{m}{kPa} \, p_a \qquad \text{or} \qquad \Delta = 2.3067 \frac{ft}{psi} \, p_a$$

where $\Delta$ is given in units of meters or feet and the applied air pressure, $p_a$, is given in units of kPa or psi.

The submersible pressure transducer that monitors the water level in the casing must be placed at a depth such that it remains submerged during the pressurized part of the test. Therefore, for the applied air pressure, $p_a$, the submersible pressure transducer should be placed below the static-water level by a distance greater than $\Delta$. In addition, the range of the pressure transducer should be sufficient to withstand the pressure associated with the column of water above the pressure transducer.

To conduct the air-pressurized slug test, the well head apparatus is attached to the well casing with an air-tight seal, a static water level measurement is made and the submersible pressure transducer is placed below the static-water level. The air-delivery system is then attached to the well-head apparatus using one or more pressure regulators between the air tanks or the air compressor (figure 2).

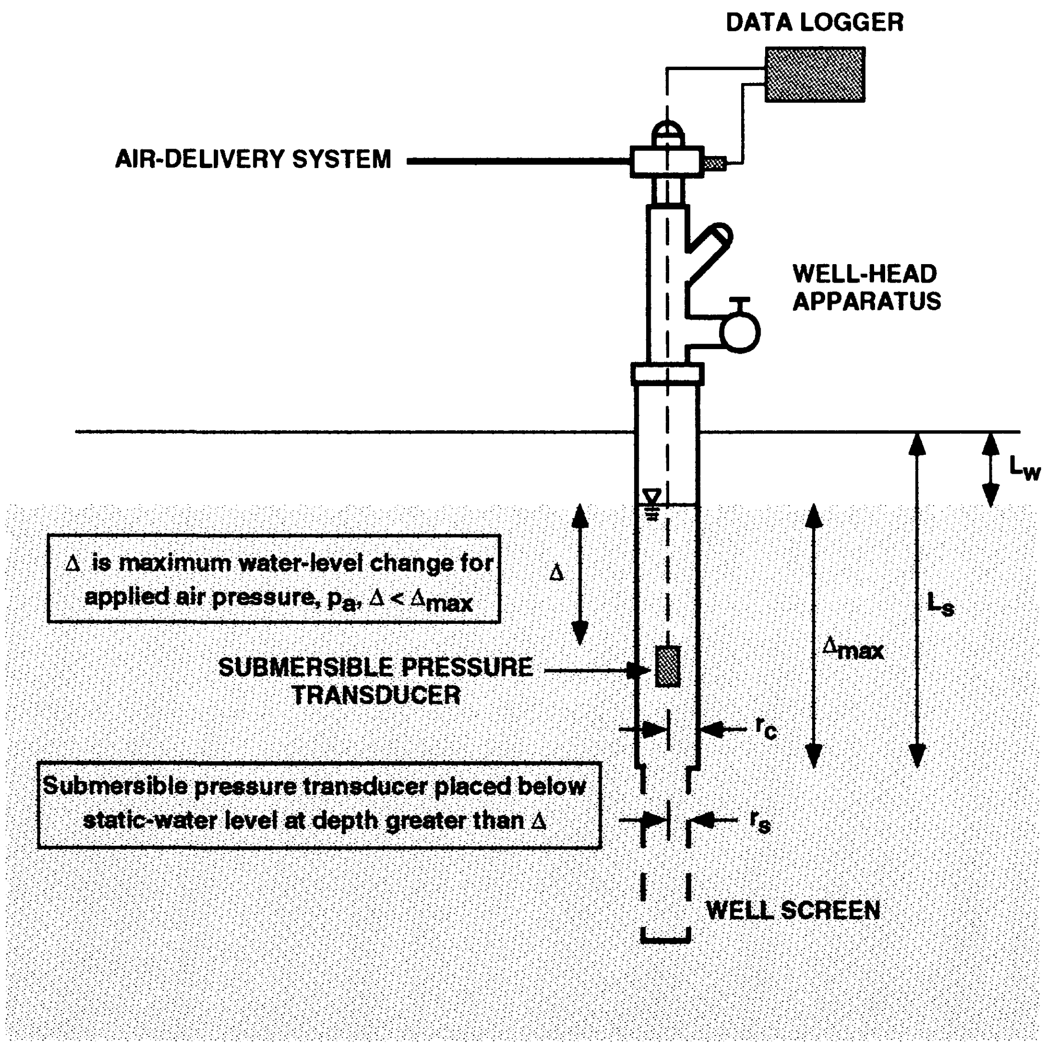


**Figure 5.** Diagram of well information needed to conduct air-pressurized slug tests and the placement of the submersible pressure transducer.

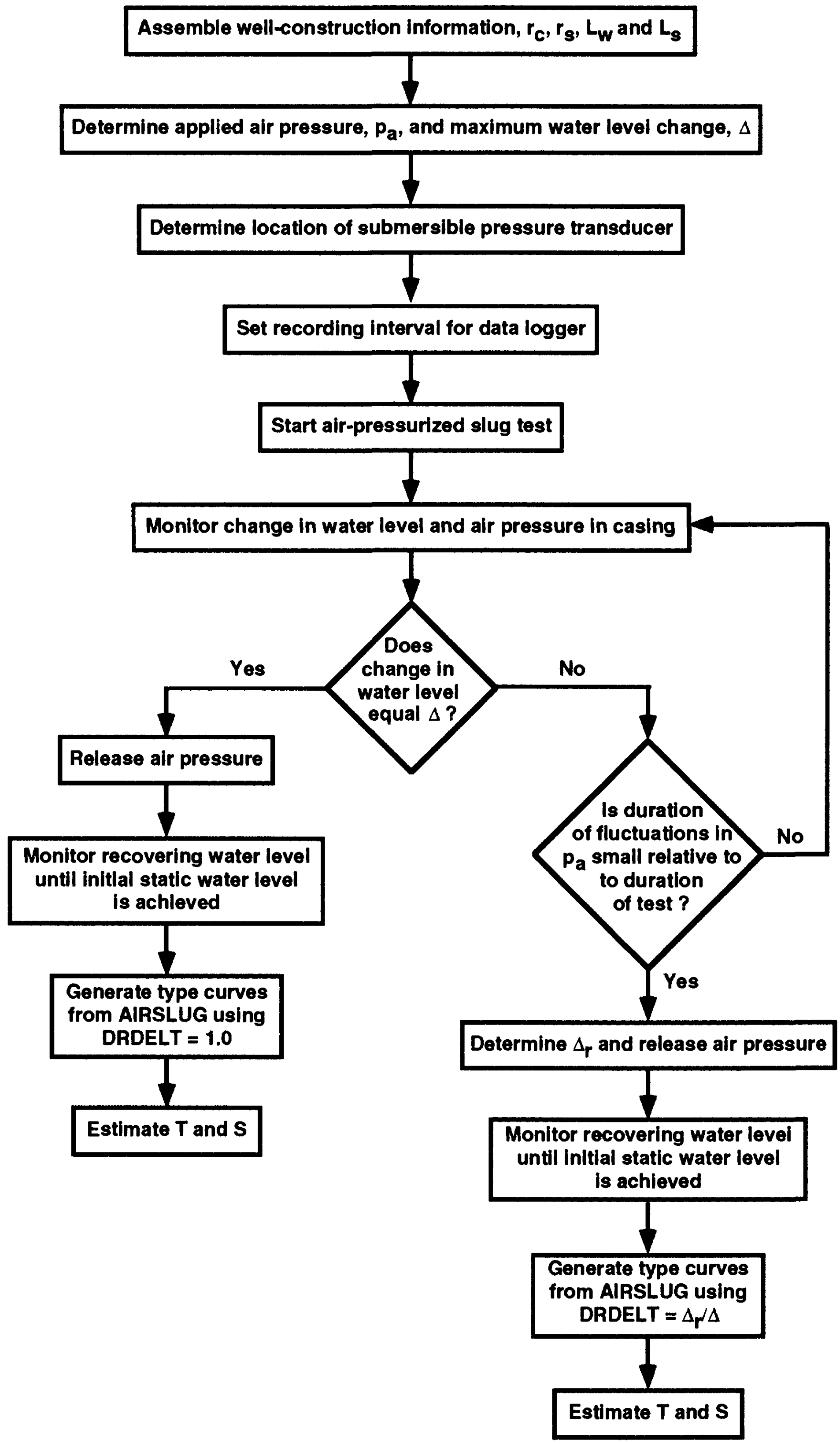


**Figure 6.** Outline of procedure for conducting air-pressurized slug tests.

Prior to pressurizing the casing, the recording interval for the pressure transducers must be set within the data loggers. At the start of the pressurized and recovery parts of the test, water levels change more rapidly than at later times in the test. Furthermore, the recording interval will depend on the permeability of the formation. In low-permeability formations, the water level will change less rapidly than in high-permeability formations. Consequently, the hydrologist conducting the air-pressurized slug test will have to choose an initial recording interval for the test and alter it based on prevailing conditions during the test. In general, it is better to acquire data rapidly at short time intervals than to have sparse data which does not distinguish the temporal variation of the water level and the applied air pressure.

To start the air-pressurized slug test, the casing is pressurized and maintained at a constant air pressure. Because the interpretation of the air-pressurized slug test in this report is based on a constant applied air pressure, it is best if a constant air pressure can be achieved within a short time period and maintained throughout the pressurized part of the test. Although it is impossible to achieve a constant air pressure instantaneously, if the initial fluctuations in the air pressure are of a short duration relative to the total time that the well is pressurized, the initial fluctuations in the air pressure will have a negligible impact on the interpretation (Shapiro and Greene, 1995).

For the applied air pressure, $p_a$, the maximum water-level change will be $\Delta$. If the water level has declined by $\Delta$, the pressurized portion of the slug test can be terminated by simultaneously opening the quick-release valve and shutting the air inflow into the casing (figure 2). The rising water level in the casing is then recorded using the pressure transducer and the data logger. Manual measurements of the water level during the recovery part of the test also can be made through the access port on the well-head apparatus. The rising water level in the well should be recorded until the initial static-water level, H, is achieved.

In low-permeability formations, it may take a significant period of time to achieve the maximum water-level change, $\Delta$, for the applied air pressure, $p_a$. Under these circumstances, the hydrologist conducting the test may choose to terminate the pressurized part of the test prior to achieving the maximum water-level change, and then interpret the rising water level using type curves developed by Shapiro and Greene (1995). The pressurized part of the test is terminated by simultaneously opening the quick-release valve and shutting off the air inflow into the casing. The time at which the pressurized part of the test is terminated is referred to as $t_r$, and the change in the water level at $t_r$ is referred to as $\Delta_r$. During the recovery part of the test, the rising water level in the casing is recorded until the initial static-water level, H, is achieved.

There are no prescribed limits on choosing $t_r$ or $\Delta_r$ if the pressurized part of the test is terminated prior to achieving the equilibrium-water level for the applied air pressure. The only specification on terminating the air-pressurized slug test prior to achieving the maximum water-level change is that the applied air pressure must be constant throughout the pressurized part of the test. Therefore, the duration of any fluctuations in the applied air pressure incurred at the initial stages of the pressurized part of the test must be small relative to the total duration of the pressurized part of the test.

If the formation is homogeneous in the vicinity of the well, terminating the pressurized part of the test for different values of $\Delta_r$ should not effect the estimation of transmissivity and storativity. Different values of $\Delta_r$ will result in a different volumes of water being forced into the formation, and thus different radii of influence in the formation. It is advantageous to hydraulically stress as large a volume of the formation as possible in estimating transmissivity and storativity, however, increasing $\Delta_r$ only will result in a small increase in the volume of the formation that is stressed hydraulically. Because slug tests are conducted to provide rough estimates of formation properties in a timely manner, the hydrologist conducting the test should consider the duration of the test in deciding when to terminate the pressurized part of the test.

## TYPE CURVES AND ESTIMATION OF TRANSMISSIVITY AND STORATIVITY

Shapiro and Greene (1995) developed a method of estimating formation properties from air-pressurized slug tests by deriving a solution to the governing equations for water level changes in a well during the pressurized and recovery parts of the test. Type curves were generated from the solution for comparison with the rising water levels. A summary of the assumptions underlying the mathematical development presented by Shapiro and Greene (1995) is discussed in the Appendix A; the reader is referred to Shapiro and Greene (1995) for additional details on the solution procedure.

To estimate formation properties, type curves are generated from equation (A.9) in Appendix A using the Fortran code AIRSLUG (Appendix B), and compared with measured water levels obtained from the recovery part of the air-pressurized slug test. Curve matching to estimate transmissivity, T, and storativity, S, is conducted similarly to that discussed by Cooper and others (1967).

### Data Preparation

To estimate transmissivity and storativity using type curves, the water-level data collected during the recovery part of the slug test must be converted to the dimensionless drawdown, $(H - w)/\Delta$, and plotted as a function of the elapsed time from the start of the recovery part of the test, $(t-t_r)$, where H is the initial static-water level, w is the time-varying water level in the casing and $\Delta$ is the maximum water-level change for the applied air pressure. The dimensionless drawdown is plotted on the vertical axis and the logarithm of time, $\log_{10}(t-t_r)$, is plotted on the horizontal axis. The range for the vertical axis is 0 to $\Delta_r/\Delta$, where $\Delta_r$ is the change in the water level in the well at the end of the pressurized part of the test. The term $\Delta_r/\Delta$ is the fraction of the maximum water-level change for the applied air pressure. For $\Delta_r/\Delta = 1$, the maximum water-level change for the applied air pressure is achieved, while for $\Delta_r/\Delta < 1$, the pressurized part of the slug test is terminated prior to achieving the maximum water-level change. The range and dimension of the horizontal axis must be the same as the range and dimension of horizontal axis of the type curves (commonly 5 order of magnitude) used to estimate T and S (see the discussion in the following section).

An example of data collected during the pressurized and recovery parts of an air-pressurized slug test is shown in table 1. These data were collected during an air-pressurized slug test conducted in the Spearfish-East Madison well in the Madison aquifer near Spearfish, South Dakota. In this test, the depth to the initial static-water level, $L_w$ , was 33.56 m (110.1 ft), and the depth to the open interval of the well, $L_s$, is

173.74 m (570 ft), thus $\Delta_{max} = L_s - L_w$= 140.18 m (459.9 ft). In this test, the datum used as a reference for water levels is the top of the open interval of the well. In general, any datum can be chosen as a reference for levels, however, it is recommended that the top of the well screen or open interval be used, because negative values will indicate water levels that have dropped below the top of the well screen or open interval. Tests where water levels have dropped below the top of the well screen cannot be interpreted by the methods discussed in this report. Because the top of the well screen is used as the datum, the initial static-water level, H, is 140.18 m (459.9 ft).

For the data shown in table 1, an applied air pressure, $p_a$, equal to 28.27 kPa (4.1 psi) was used to pressurize the column of air in the well. This corresponds to an anticipated maximum water-level change, $\Delta$, equal to 2.88 m (0.1020 m/kPa x 28.27 kPa or 9.46 ft = 2.3067 ft/psi x 4.1 psi). A 103.43 kPa (15 psi) pressure transducer was placed 4.57 m (15 ft) below the static water level, which is greater than $\Delta$, but not greater than the range of the submersible pressure transducer. The duration of the pressurized part of the test was 100 minutes. The pressurized part of the test was terminated when the water level in the well, w, was 138.58 m (454.65 ft) above the open interval. This corresponds to a value for $\Delta_r$ equal to 1.60 m (5.25 ft). Because the test was terminated prior to reaching the maximum water-level change for the applied air pressure, this test was a prematurely terminated air-pressured slug test where $\Delta_r/\Delta$ equals 0.56 = (1.60 m/2.88 m or 5.25 ft/9.46 ft).

In table 1, Columns A-D are the data that are usually collected during the air-pressurized slug test. Columns A and B are the date and time of each measurement, column C is the air pressure in the well casing obtained from the nonsubmersible pressure transducer, and Column D is the water level in the well measured by the submersible pressure transducer, where the water level is measured with respect to the top of the open interval of the well. During the pressurized part of the test, the submersible pressure transducer measures the combined pressure of the column of water above the transducer and the applied air pressure. Therefore, to calculate the water level in the casing during the pressurized part of the test, the air pressure in the casing is subtracted from the pressure transducer reading.

In table 1, Columns E and F are data computed during the recovery part of the test. Column E is the elapsed time from the start of the recovery part of the test and Column F is the dimensionless drawdown during the recovery part of the test. Column G contains comments describing the different parts of the air-pressurized slug test. A plot of the dimensionless drawdown during the recovery part of the test from table 1 is shown in figure 7.

**Table 1.** Data collected from the pressurized and recovery parts of an air-pressurized slug test conducted in the Spearfish-East Madison well near Spearfish, South Dakota [$p_a$ = 28.27 kPa (4.1 psi); $\Delta$ = 2.88 m (9.46 ft); $L_w$ = 33.56 m (110.1 ft); $L_s$ =173.74 m (570.0 ft); $r_c$= 0.064 m (0.21 ft); $r_s$ = 0.060 m (0.20 ft); water level is referenced to the top of the open interval of the well].

| A | B | C | | D | | E | F | G |
|---|---|---|---|---|---|---|---|---|
| Date, in Mon/Day/Yr | Time, in Hr:Min:Sec | Air Pressure in Casing, | | Water Level above top of open interval, w, | | Elapsed Time from the start of recovery, $t - t_r$, in minutes | Dimensionless Drawdown, $(H - w)/\Delta$ | Comments |
| | | kPa | psi | m | ft | | | |
| 6/15/93 | 10:48:00 | 0.00 | 0.00 | 140.18 | 459.90 | | | Pre-test measurement |
| 6/15/93 | 11:00:00 | 0.00 | 0.00 | 140.18 | 459.90 | | | |
| 6/15/93 | 11:18:00 | 0.00 | 0.00 | 140.18 | 459.90 | | | |
| 6/15/93 | 11:18:54 | 0.00 | 0.00 | 140.18 | 459.90 | | | Start pressurizing casing |
| 6/15/93 | 11:19:57 | 0.69 | 0.10 | 140.18 | 459.90 | | | Pressurized part of test |
| 6/15/93 | 11:20:03 | 3.44 | 0.50 | 139.99 | 459.30 | | | |
| 6/15/93 | 11:20:06 | 15.31 | 2.22 | 139.72 | 458.39 | | | |
| 6/15/93 | 11:20:09 | 20.20 | 2.93 | 139.77 | 458.55 | | | |
| 6/15/93 | 11:20:12 | 22.27 | 3.23 | 139.79 | 458.62 | | | |
| 6/15/93 | 11:20:15 | 27.65 | 4.01 | 139.89 | 458.96 | | | |
| 6/15/93 | 11:20:18 | 28.68 | 4.16 | 139.91 | 459.02 | | | |
| 6/15/93 | 11:20:21 | 27.79 | 4.03 | 139.83 | 458.76 | | | |
| 6/15/93 | 11:20:24 | 27.10 | 3.93 | 139.83 | 458.76 | | | |
| 6/15/93 | 11:20:27 | 27.30 | 3.96 | 139.74 | 458.46 | | | |
| 6/15/93 | 11:20:30 | 27.86 | 4.04 | 139.67 | 458.22 | | | |
| 6/15/93 | 11:20:33 | 27.86 | 4.04 | 139.67 | 458.22 | | | |
| 6/15/93 | 11:20:36 | 27.86 | 4.04 | 139.65 | 458.18 | | | |
| 6/15/93 | 11:20:39 | 27.92 | 4.05 | 139.66 | 458.20 | | | |
| 6/15/93 | 11:20:42 | 27.92 | 4.05 | 139.65 | 458.18 | | | |
| 6/15/93 | 11:20:45 | 28.06 | 4.07 | 139.64 | 458.14 | | | |
| 6/15/93 | 11:20:48 | 28.13 | 4.08 | 139.63 | 458.12 | | | |
| 6/15/93 | 11:20:51 | 28.20 | 4.09 | 139.63 | 458.12 | | | |
| 6/15/93 | 11:20:54 | 28.20 | 4.09 | 139.63 | 458.12 | | | |
| 6/15/93 | 11:20:57 | 28.41 | 4.12 | 139.64 | 458.14 | | | |
| 6/15/93 | 11:21:00 | 28.47 | 4.13 | 139.86 | 458.27 | | | |
| 6/15/93 | 11:22:00 | 28.27 | 4.10 | 139.80 | 458.66 | | | |
| 6/15/93 | 11:23:00 | 28.55 | 4.14 | 139.78 | 458.64 | | | |
| . | . | . | . | . | . | | | |
| . | . | . | . | . | . | | | |
| . | . | . | . | . | . | | | |
| 6/15/93 | 11:35:00 | 28.75 | 4.17 | 139.57 | 457.91 | | | |

**Table 1 (continued).** Data collected from the pressurized and recovery parts of an air-pressurized slug test conducted in the Spearfish-East Madison well near Spearfish, South Dakota.

| A | B | C | | D | | E | F | G |
|---|---|---|---|---|---|---|---|---|
| Date, in Mon/Day/Yr | Time, in Hr:Min:Sec | Air Pressure in Casing, | | Water Level above top of open interval, w, | | Elapsed Time from the start of recovery, $t - t_r$, in minutes | Dimensionless Drawdown, (H - w)/Δ | Comments |
| | | kPa | psi | m | ft | | | |
| . | . | . | . | . | . | | | |
| 6/15/93 | 11:40:00 | 28.34 | 4.þl | 139.49 | 457.67 | | | Pressurized art of test |
| . | . | . | . | . | . | | | |
| 6/15/93 | 12:00:00 | 28.20 | 4.09 | 139.15 | 456.52 | | | |
| . | . | . | . | . | . | | | |
| 6/15/93 | 12:56:00 | 28.20 | 4.09 | 138.61 | 454.76 | | | |
| 6/15/93 | 12:57:00 | 28.20 | 4.09 | 138.60 | 454.72 | | | |
| 6/15/93 | 12:58:00 | 28.20 | 4.09 | 138.59 | 454.69 | | | |
| 6/15/93 | 12:59:00 | 28.20 | 4.09 | 138.58 | 454.65 | | | Release air pressure in casing |
| 6/15/93 | 13:00:16 | 0.00 | 0.00 | 138.60 | 454.74 | 1.27 | 0.55 | Recovery part of test |
| 6/15/93 | 13:00:30 | 0.00 | 0.00 | 138.60 | 454.74 | 1.50 | 0.55 | |
| 6/15/93 | 13:01:00 | 0.00 | 0.00 | 138.64 | 454.85 | 2.00 | 0.53 | |
| 6/15/93 | 13:01:30 | 0.00 | 0.00 | 138.66 | 454.93 | 2.50 | 0.53 | |
| 6/15/93 | 13:02:00 | 0.00 | 0.00 | 138.67 | 454.97 | 3.00 | 0.52 | |
| 6/15/93 | 13:03:00 | 0.00 | 0.00 | 138.70 | 455.04 | 4.00 | 0.51 | |
| 6/15/93 | 13:04:00 | 0.00 | 0.00 | 138.72 | 455.12 | 5.00 | 0.51 | |
| 6/15/93 | 13:05:00 | 0.00 | 0.00 | 138.74 | 455.19 | 6.00 | 0.50 | |
| 6/15/93 | 13:07:00 | 0.00 | 0.00 | 138.79 | 455.34 | 8.00 | 0.48 | |
| 6/15/93 | 13:09:00 | 0.00 | 0.00 | 138.82 | 455.45 | 10.00 | 0.47 | |
| 6/15/93 | 13:11:00 | 0.00 | 0.00 | 138.58 | 455.57 | 12.00 | 0.46 | |
| 6/15/93 | 13:14:00 | 0.00 | 0.00 | 138.88 | 455.64 | 15.00 | 0.45 | |
| 6/15/93 | 13:16:00 | 0.00 | 0.00 | 138.92 | 455.79 | 17.00 | 0.43 | |
| 6/15/93 | 13:19:00 | 0.00 | 0.00 | 138.97 | 455.94 | 20.00 | 0.42 | |
| 6/15/93 | 13:24:00 | 0.00 | 0.00 | 139.03 | 456.13 | 25.00 | 0.40 | |
| 6/15/93 | 13:29:00 | 0.00 | 0.00 | 139.07 | 456.28 | 30.00 | 0.38 | |
| 6/15/93 | 13:34:00 | 0.00 | 0.00 | 139.13 | 456.47 | 35.00 | 0.36 | |

**Table 1 (continued).** Data collected from the pressurized and recovery parts of an air-pressurized slug test conducted in the Spearfish-East Madison well near Spearfish, South Dakota.

| A | B | C | | D | | E | F | G |
|---|---|---|---|---|---|---|---|---|
| Date, in Mon/Day/Yr | Time, in Hr:Min:Sec | Air Pressure in Casing, | | Water Level above top of open interval, w, | | Elapsed Time from the start of recovery, $t - t_r$, in minutes | Dimensionless Drawdown, $(H - w)/\Delta$ | Comments |
| | | kPa | psi | m | ft | | | |
| 6/15/93 | 13:39:00 | 0.00 | 0.00 | 139.18 | 456.62 | 40.00 | 0.35 | Recovery part of test |
| 6/15/93 | 13:49:00 | 0.00 | 0.00 | 139.24 | 456.84 | 50.00 | 0.32 | |
| 6/15/93 | 13:59:00 | 0.00 | 0.00 | 139.34 | 457.14 | 60.00 | 0.29 | |
| 6/15/93 | 14:08:00 | 0.00 | 0.00 | 139.40 | 457.36 | 69.00 | 0.27 | |
| 6/15/93 | 14:21:00 | 0.00 | 0.00 | 139.49 | 457.63 | 82.00 | 0.24 | |
| 6/15/93 | 14:39:00 | 0.00 | 0.00 | 139.53 | 457.79 | 100.00 | 0.22 | |
| 6/15/93 | 14:59:00 | 0.00 | 0.00 | 139.61 | 458.03 | 120.00 | 0.20 | |
| 6/15/93 | 15:29:00 | 0.00 | 0.00 | 139.72 | 458.39 | 150.00 | 0.16 | |
| 6/15/93 | 15:54:00 | 0.00 | 0.00 | 139.78 | 458.61 | 175.00 | 0.14 | |
| 6/15/93 | 16:44:00 | 0.00 | 0.00 | 139.88 | 458.93 | 225.00 | 0.10 | |
| 6/15/93 | 17:59:00 | 0.00 | 0.00 | 139.98 | 459.26 | 300.00 | 0.07 | |
| 6/15/93 | 19:39:00 | 0.00 | 0.00 | 140.07 | 459.54 | 400.00 | 0.04 | |
| 6/15/93 | 21:19:00 | 0.00 | 0.00 | 140.10 | 459.66 | 500.00 | 0.03 | |
| 6/15/93 | 22:59:00 | 0.00 | 0.00 | 140.13 | 459.73 | 600.00 | 0.02 | |
| 6/16/93 | 0:39:00 | 0.00 | 0.00 | 140.15 | 459.81 | 700.00 | 0.01 | |
| 6/16/93 | 2:09:00 | 0.00 | 0.00 | 140.16 | 459.84 | 790.00 | 0.01 | End test |

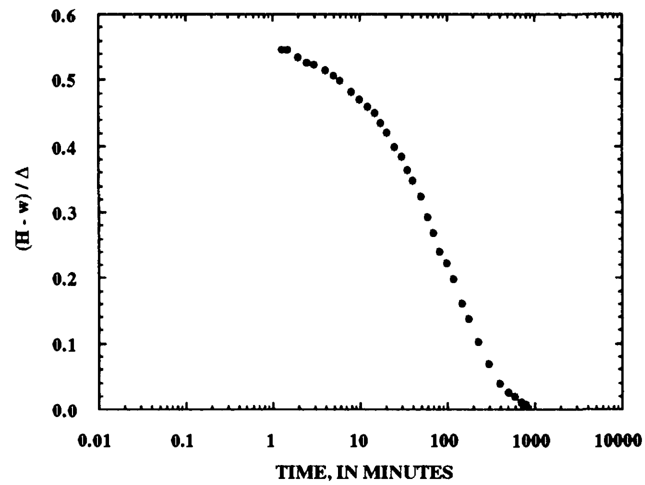


**Figure 7.** Dimensionless drawdown data from an air-pressurized slug test conducted in the Spearfish-East Madison well near Spearfish, South Dakota.

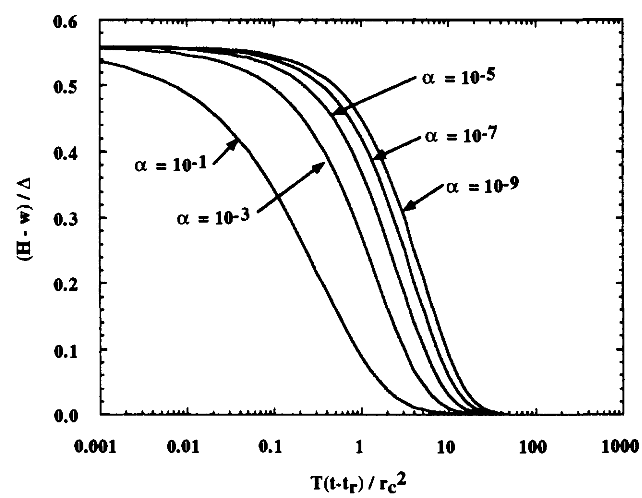


**Figure 8.** Type curves generated from the FORTRAN program AIRSLUG for $\Delta_r/\Delta = 0.56$.

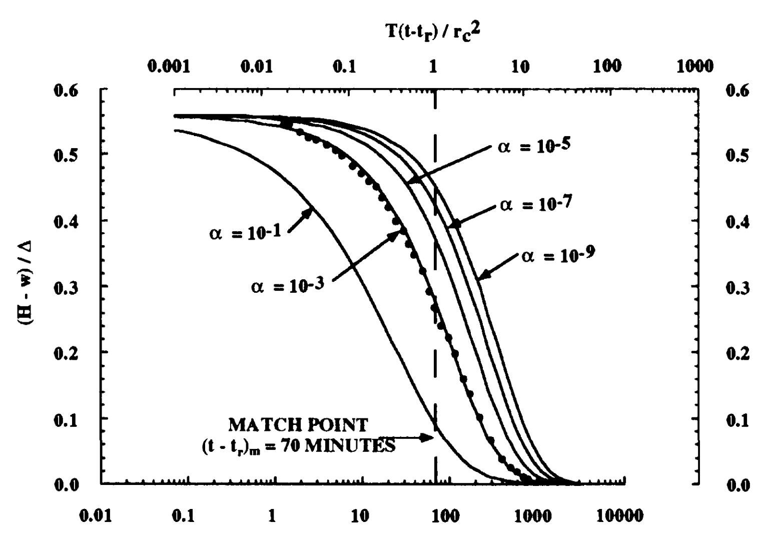


**Figure 9.** Composite plot of type curves and drawdown data from an air-pressurized slug test conducted in the Spearfish-East Madison well near Spearfish, South Dakota.

## Type Curves

The Fortran program AIRSLUG was developed to compute the solution given by Shapiro and Greene (1995) for the preparation of type curves needed to estimate T and S from water-level data collected during the recovery part of air-pressurized slug tests. An MS DOS formatted diskette with an ASCII listing and a compiled (.EXE) version of AIRSLUG is enclosed in this document. A listing of the Fortran code also is given in the Appendix B. The type curves generated from AIRSLUG are the theoretical, time-varying, dimensionless drawdown in a well during the recovery part of a prematurely terminated air-pressurized slug test. By visually fitting the theoretical drawdown to the measured drawdown, the aquifer properties which best fit the data can be estimated.

To generate the type curves that are appropriate for comparison with the measured water levels, the user must specify the measured value of $\Delta_r/\Delta$, which is referred to as the variable DRDELT in AIRSLUG. For a given value of DRDELT, the program generates values of the dimensionless drawdown for 9 type curves, where each type curve is associated with a value of the dimensionless parameter $\alpha = S\ r_c^2/r_s^2$, ( $\alpha = 10^{-1}, 10^{-2}, \ldots 10^{-9}$); $\alpha$ defines the ratio of the storage in the formation per unit volume to the storage in the borehole per unit volume. The results are stored in a file named by the user. The user can then generate plots of the type curves using external software packages. The values defining the type curves are listed in 10 columns. The first column contains dimensionless times, $T(t - t_r)/r_c^2$, at which the dimensionless drawdowns are evaluated. Columns 2 through 10 contain dimensionless drawdowns for the dimensionless times given in the first column; each column corresponds to a type curve for a different value of $\alpha$, $\alpha = 10^{-1}, 10^{-2}, \ldots 10^{-9}$.

The user of AIRSLUG alternatively can specify that a single type curve be generated for a specific value of $\alpha$. In this case, the program will generate values for only one type curve and store them in a file named by the user. The values defining the type curve will be listed in 2 columns; the first column contains the dimensionless time and the second column contains the dimensionless drawdowns for the specified value of $\alpha$.

The type curves are plotted similarly to the dimensionless drawdown computed from the measured water levels. The dimensionless drawdown is plotted on the vertical axis and the logarithm of the dimensionless time, $\log_{10}[T(t - t_r)/r_c^2]$, is plotted on the horizontal axis. The range of the dimensionless drawdown on the vertical axis is 0 to $\Delta_r/\Delta$, and the range of the dimensionless time on the horizontal axis is 5 orders of magnitude, $10^{-3} < T(t - t_r)/r_c^2 < 10^2$.

An example of type curves generated using AIRSLUG is shown in figure 8. The type curves in figure 8 were generated to interpret the data from the air-pressurized slug test shown in table 1. The test was terminated for $\Delta_r/\Delta$ equal to 0.56; thus, the user would specify DRDELT equal to 0.56 in AIRSLUG to generate the type curves. Table 2 shows the output of AIRSLUG for DRDELT equal to 0.56.

**Table 2.** Values of dimensionless drawdown generated from AIRSLUG for $\Delta_r/\Delta = 0.56$ used in preparing type curves to interpret the measured drawdown during an air-pressurized slug test $[\alpha = Sr_c^2/r_s^2]$.

| Dimensionless Time $\frac{T(t-t_r)}{r_c^2}$ | Dimensionless Water Level, (H - w)/Δ $\alpha = 10^{-1}$ | $\alpha = 10^{-2}$ | $\alpha = 10^{-3}$ | $\alpha = 10^{-4}$ | $\alpha = 10^{-5}$ | $\alpha = 10^{-6}$ | $\alpha = 10^{-7}$ | $\alpha = 10^{-8}$ | $\alpha = 10^{-9}$ |
|---|---|---|---|---|---|---|---|---|---|
| 0.10000E-02 | .53717 | .55213 | .55699 | .55857 | .55918 | .55944 | .55956 | .55964 | .55969 |
| 0.11220E-02 | .53582 | .55165 | .55678 | .55846 | .55912 | .55939 | .55952 | .55961 | .55967 |
| 0.12589E-02 | .53438 | .55118 | .55655 | .55834 | .55904 | .55934 | .55948 | .55958 | .55964 |
| 0.14125E-02 | .53286 | .55049 | .55630 | .55821 | .55896 | .55928 | .55944 | .55955 | .55961 |
| 0.15849E-02 | .53125 | .54992 | .55603 | .55807 | .55887 | .55922 | .55939 | .55951 | .55958 |
| 0.17783E-02 | .52954 | .54926 | .55574 | .55791 | .55877 | .55914 | .55934 | .55946 | .55954 |
| 0.19953E-02 | .52773 | .54857 | .55543 | .55774 | .55866 | .55907 | .55928 | .55941 | .55950 |
| 0.22387E-02 | .52581 | .54783 | .55510 | .55756 | .55854 | .55898 | .55921 | .55936 | .55946 |
| 0.25119E-02 | .52378 | .54703 | .55473 | .55735 | .55840 | .55888 | .55913 | .55930 | .55941 |
| 0.28184E-02 | .52162 | .54618 | .55434 | .55713 | .55826 | .55878 | .55905 | .55923 | .55935 |
| 0.31623E-02 | .51934 | .54527 | .55391 | .55689 | .55810 | .55866 | .55896 | .55916 | .55929 |
| 0.35481E-02 | .51692 | .54430 | .55345 | .55662 | .55792 | .55853 | .55886 | .55908 | .55922 |
| 0.39811E-02 | .51436 | .54325 | .55295 | .55633 | .55773 | .55839 | .55875 | .55899 | .55915 |
| 0.44668E-02 | .51165 | .54213 | .55241 | .55602 | .55752 | .55823 | .55863 | .55889 | .55906 |
| 0.50119E-02 | .50878 | .54093 | .55182 | .55567 | .55728 | .55806 | .55849 | .55877 | .55897 |
| 0.56234E-02 | .50574 | .53965 | .55118 | .55529 | .55703 | .55787 | .55834 | .55865 | .55886 |
| 0.63096E-02 | .50252 | .53827 | .55049 | .55488 | .55674 | .55766 | .55817 | .55851 | .55875 |
| 0.70795E-02 | .49911 | .53680 | .54974 | .55443 | .55643 | .55742 | .55799 | .55836 | .55862 |
| 0.79433E-02 | .49550 | .53521 | .54893 | .55393 | .55609 | .55717 | .55778 | .55819 | .55847 |
| 0.89125E-02 | .49168 | .53351 | .54805 | .55339 | .55571 | .55688 | .55756 | .55801 | .55831 |
| 0.10000E-01 | .48764 | .53169 | .54709 | .55279 | .55529 | .55657 | .55731 | .55780 | .55814 |
| 0.11220E-01 | .48355 | .52974 | .54605 | .55214 | .55484 | .55622 | .55703 | .55757 | .55794 |
| 0.12589E-01 | .47968 | .52764 | .54492 | .55143 | .55433 | .55584 | .55672 | .55731 | .55772 |
| 0.14125E-01 | .47373 | .52538 | .54369 | .55065 | .55378 | .55541 | .55638 | .55703 | .55748 |
| 0.15849E-01 | .46904 | .52296 | .54236 | .54980 | .55317 | .55494 | .55600 | .55671 | .55721 |
| 0.17783E-01 | .46362 | .52036 | .54091 | .54886 | .55250 | .55443 | .55559 | .55636 | .55691 |
| 0.19953E-01 | .45806 | .51758 | .53933 | .54783 | .55176 | .55386 | .55512 | .55598 | .55658 |
| 0.22387E-01 | .45217 | .51458 | .53762 | .54671 | .55094 | .55322 | .55461 | .55555 | .55621 |
| 0.25119E-01 | .44593 | .51137 | .53576 | .54548 | .55005 | .55253 | .55404 | .55507 | .55580 |
| 0.28184E-01 | .43936 | .50792 | .53373 | .54413 | .54906 | .55176 | .55341 | .55454 | .55535 |
| 0.31623E-01 | .43243 | .50421 | .53153 | .54265 | .54797 | .55090 | .55272 | .55396 | .55484 |
| 0.35481E-01 | .42516 | .50024 | .52914 | .54103 | .54677 | .54996 | .55195 | .55331 | .55428 |
| 0.39811E-01 | .41750 | .49597 | .52655 | .53926 | .54546 | .54893 | .55110 | .55259 | .55366 |
| 0.44668E-01 | .40947 | .49140 | .52372 | .53732 | .54401 | .54778 | .55015 | .55179 | .55297 |
| 0.50119E-01 | .40105 | .48650 | .52066 | .53519 | .54241 | .54651 | .54911 | .55090 | .55220 |
| 0.56234E-01 | .39224 | .48125 | .51733 | .53286 | .54065 | .54512 | .54795 | .54992 | .55135 |
| 0.63096E-01 | .38302 | .47562 | .51372 | .53032 | .53872 | .54357 | .54668 | .54883 | .55040 |
| 0.70795E-01 | .37340 | .46961 | .50979 | .52753 | .53660 | .54187 | .54526 | .54762 | .54935 |
| 0.79433E-01 | .36337 | .46317 | .50554 | .52448 | .53426 | .53999 | .54370 | .54629 | .54818 |
| 0.89125E-01 | .35294 | .45629 | .50093 | .52115 | .53169 | .53792 | .54197 | .54481 | .54689 |

**Table 2 (continued).** Values of dimensionless drawdown generated from AIRSLUG for $\Delta_r/\Delta$ = 0.56 used in preparing type curves to interpret the measured drawdown during an air-pressurized slug test [$\alpha = Sr_c^2/r_s^2$].

| Dimensionless Time $\frac{T(t - t_r)}{r_c^2}$ | Dimensionless Water Level, (H - w)/Δ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\alpha = 10^{-1}$ | $\alpha = 10^{-2}$ | $\alpha = 10^{-3}$ | $\alpha = 10^{-4}$ | $\alpha = 10^{-5}$ | $\alpha = 10^{-6}$ | $\alpha = 10^{-7}$ | $\alpha = 10^{-8}$ | $\alpha = 10^{-9}$ |
| 0.10000E+00 | .34210 | .44895 | .49593 | .51751 | .52887 | .53564 | .54006 | .54317 | .54546 |
| 0.11220E+00 | .33087 | .44112 | .49052 | .51353 | .52578 | .53312 | .53794 | .54135 | .54387 |
| 0.12589E+00 | .31926 | .43279 | .48467 | .50919 | .52238 | .53035 | .53561 | .53934 | .54211 |
| 0.14125E+00 | .30729 | .42392 | .47834 | .50445 | .51865 | .52729 | .53304 | .53712 | .54016 |
| 0.15849E+00 | .29497 | .41451 | .47151 | .49929 | .51456 | .52393 | .53019 | .53466 | .53799 |
| 0.17783E+00 | .28233 | .40453 | .46415 | .49367 | .51008 | .52024 | .52706 | .53195 | .53560 |
| 0.19953E+00 | .26941 | .39397 | .45621 | .48755 | .50518 | .51617 | .52360 | .52894 | .53295 |
| 0.22387E+00 | .25625 | .38282 | .44768 | .48091 | .49982 | .51171 | .51979 | .52563 | .53002 |
| 0.25119E+00 | .24288 | .37107 | .43852 | .47370 | .49397 | .50682 | .51560 | .52197 | .52678 |
| 0.28184E+00 | .22935 | .35872 | .42870 | .46588 | .48758 | .50145 | .51099 | .51794 | .52320 |
| 0.31623E+00 | .21573 | .34578 | .41820 | .45743 | .48061 | .49557 | .50592 | .51349 | .51924 |
| 0.35481E+00 | .20206 | .33226 | .40699 | .44829 | .47303 | .48914 | .50035 | .50860 | .51488 |
| 0.39811E+00 | .18842 | .31818 | .39506 | .43844 | .46479 | .48211 | .49425 | .50321 | .51008 |
| 0.44668E+00 | .17487 | .30357 | .38238 | .42785 | .45586 | .47444 | .48757 | .49730 | .50478 |
| 0.50119E+00 | .16148 | .28847 | .36897 | .41647 | .44618 | .46609 | .48026 | .49081 | .49896 |
| 0.56234E+00 | .14833 | .27292 | .35481 | .40429 | .43572 | .45702 | .47227 | .48370 | .49256 |
| 0.63096E+00 | .13548 | .25700 | .33992 | .39129 | .42445 | .44717 | .46357 | .47592 | .48554 |
| 0.70795E+00 | .12302 | .24078 | .32433 | .37746 | .41234 | .43651 | .45410 | .46743 | .47785 |
| 0.79433E+00 | .11101 | .22434 | .30807 | .36278 | .39935 | .42499 | .44381 | .45817 | .46944 |
| 0.89125E+00 | .09952 | .20778 | .29120 | .34728 | .38547 | .41259 | .43267 | .44809 | .46026 |
| 0.10000E+01 | .08861 | .19121 | .27379 | .33098 | .37069 | .39927 | .42064 | .43716 | .45026 |
| 0.11220E+01 | .07834 | .17475 | .25592 | .31391 | .35502 | .38503 | .40768 | .42532 | .43940 |
| 0.12589E+01 | .06874 | .15852 | .23770 | .29614 | .33848 | .36984 | .39376 | .41254 | .42762 |
| 0.14125E+01 | .05986 | .14266 | .21924 | .27774 | .32109 | .35371 | .37888 | .39880 | .41489 |
| 0.15849E+01 | .05171 | .12730 | .20070 | .25881 | .30292 | .33667 | .36302 | .38406 | .40118 |
| 0.17783E+01 | .04431 | .11256 | .18223 | .23947 | .28405 | .31876 | .34621 | .36833 | .38646 |
| 0.19953E+01 | .03766 | .09858 | .16399 | .21987 | .26457 | .30003 | .32846 | .35160 | .37072 |
| 0.22387E+01 | .03174 | .08546 | .14616 | .20016 | .24461 | .28058 | .30984 | .33391 | .35397 |
| 0.25119E+01 | .02653 | .07329 | .12892 | .18055 | .22433 | .26052 | .29041 | .31530 | .33623 |
| 0.28184E+01 | .02200 | .06216 | .11246 | .16122 | .20390 | .23999 | .27030 | .29585 | .31755 |
| 0.31623E+01 | .01809 | .05211 | .09693 | .14238 | .18352 | .21915 | .24962 | .27565 | .29800 |
| 0.35481E+01 | .01476 | .04318 | .08249 | .12426 | .16342 | .19822 | .22854 | .25484 | .27767 |
| 0.39811E+01 | .01196 | .03535 | .06927 | .10706 | .14382 | .17739 | .20726 | .23357 | .25670 |
| 0.44668E+01 | .00962 | .02859 | .05735 | .09097 | .12496 | .15693 | .18600 | .21205 | .23525 |
| 0.50119E+01 | .00769 | .02286 | .04680 | .07617 | .10708 | .13707 | .16499 | .19048 | .21352 |
| 0.56234E+01 | .00611 | .01807 | .03762 | .06278 | .09040 | .11808 | .14451 | .16912 | .19173 |
| 0.63096E+01 | .00484 | .01414 | .02979 | .05090 | .07509 | .10019 | .12482 | .14825 | .17014 |
| 0.70795E+01 | .00381 | .01097 | .02325 | .04057 | .06131 | .08363 | .10618 | .12812 | .14902 |
| 0.79433E+01 | .00299 | .00844 | .01789 | .03177 | .04915 | .06859 | .08883 | .10903 | .12865 |
| 0.89125E+01 | .00235 | .00645 | .01359 | .02446 | .03867 | .05520 | .07299 | .09122 | .10932 |
| 0.10000E+02 | .00184 | .00491 | .01021 | .01851 | .02984 | .04355 | .05882 | .07493 | .09130 |
| 0.11220E+02 | .00143 | .00373 | .00760 | .01379 | .02257 | .03365 | .04643 | .06033 | .07482 |

**Table 2 (continued).** Values of dimensionless drawdown generated from AIRSLUG for $\Delta_r/\Delta = 0.56$ used in preparing type curves to interpret the measured drawdown during an air-pressurized slug test $[\alpha = Sr_c^2/r_s^2]$.

| Dimensionless Time $\frac{T(t - t_r)}{r_c^2}$ | Dimensionless Water Level, (H - w)/Δ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\alpha = 10^{-1}$ | $\alpha = 10^{-2}$ | $\alpha = 10^{-3}$ | $\alpha = 10^{-4}$ | $\alpha = 10^{-5}$ | $\alpha = 10^{-6}$ | $\alpha = 10^{-7}$ | $\alpha = 10^{-8}$ | $\alpha = 10^{-9}$ |
| 0.12589E+02 | .00112 | .00283 | .00563 | .01014 | .01676 | .02545 | .03586 | .04755 | .06007 |
| 0.14125E+02 | .00087 | .00215 | .00415 | .00737 | .01223 | .01885 | .02708 | .03664 | .04717 |
| 0.15849E+02 | .00068 | .00163 | .00307 | .00533 | .00879 | .01368 | .01999 | .02757 | .03618 |
| 0.17783E+02 | .00053 | .00124 | .00227 | .00384 | .00625 | .00975 | .01443 | .02024 | .02707 |
| 0.19953E+02 | .00042 | .00095 | .00169 | .00277 | .00441 | .00685 | .01020 | .01452 | .01975 |
| 0.22387E+02 | .00033 | .00073 | .00126 | .00201 | .00311 | .00476 | .00709 | .01018 | .01405 |
| 0.25119E+02 | .00026 | .00056 | .00095 | .00147 | .00221 | .00330 | .00486 | .00700 | .00976 |
| 0.28184E+02 | .00020 | .00043 | .00072 | .00108 | .00158 | .00229 | .00332 | .00474 | .00663 |
| 0.31623E+02 | .00016 | .00034 | .00055 | .00081 | .00114 | .00161 | .00227 | .00319 | .00444 |
| 0.35481E+02 | .00012 | .00026 | .00042 | .00061 | .00084 | .00114 | .00156 | .00215 | .00295 |
| 0.39811E+02 | .00010 | .00020 | .00032 | .00046 | .00062 | .00083 | .00110 | .00146 | .00196 |
| 0.44668E+02 | .00008 | .00016 | .00025 | .00035 | .00047 | .00061 | .00078 | .00101 | .00132 |
| 0.50119E+02 | .00006 | .00012 | .00019 | .00027 | .00036 | .00045 | .00057 | .00072 | .00091 |
| 0.56234E+02 | .00005 | .00010 | .00015 | .00021 | .00027 | .00034 | .00042 | .00052 | .00064 |
| 0.63096E+02 | .00004 | .00008 | .00012 | .00016 | .00021 | .00026 | .00032 | .00038 | .00046 |
| 0.70795E+02 | .00003 | .00006 | .00009 | .00013 | .00016 | .00020 | .00024 | .00029 | .00034 |
| 0.79433E+02 | .00002 | .00005 | .00007 | .00010 | .00013 | .00015 | .00018 | .00022 | .00025 |
| 0.89125E+02 | .00002 | .00004 | .00006 | .00008 | .00010 | .00012 | .00014 | .00017 | .00019 |
| 0.10000E+03 | .00001 | .00003 | .00004 | .00006 | .00008 | .00009 | .00011 | .00013 | .00015 |

## Estimating T and S

To estimate T and S, the plot of the measured drawdown and the plot of the type curves are superimposed, keeping the vertical axes of the two plots parallel and aligning the horizontal axes so that they overlay each other. The two plots are then shifted along the horizontal axis until one of the type curves, associated with a given value of $\alpha$, fits the data. A match point (in time) on the horizontal axes of the type curve and the data curve is then selected to compute the transmissivity. The match point on the horizontal axis of the type curve is referred to as $t_m' = [T(t - t_r)/r_c^2]_m$, corresponding to the time on the axis of the data curve, $(t - t_r)_m$. For convenience, the match point $t_m' = [T(t - t_r)/r_c^2]_m = 1$ on the axis of the type curve can be chosen; however, other match points will provide equivalent results.

From the match point, the transmissivity, T, is calculated using

$$T = \frac{t_m' \, r_c^2}{\left(t - t_r\right)_m}$$

The storativity, S, is calculated from the value of $\alpha$ associated with the type curve that provides the best fit to the data. The storativity is calculated from the definition of $\alpha$,

$$S = \frac{\alpha \, r_c^2}{r_s^2}$$

For the data given in table 1, figure 9 shows the superposition of the type curves and data, where the type curve for $\alpha = 10^{-3}$ provides the best fit to the data. From this fit, the match point $t_m' = [\, T(t - t_r)/r_c^2 \,]_m = 1$ on the axis of the type curve is selected, which corresponds to the time on the axis of the data curve $(t - t_r)_m = 70$ minutes. From this match point, the transmissivity is calculated to be $9.67 \times 10^{-7}$ $m^2/s$ ($0.90$ $ft^2/day$) and from the value of $\alpha$, the storativity is $1.1 \times 10^{-3}$.

## FIELD APPLICATIONS AND EXAMPLES

To illustrate the application of air-pressurized slug tests in estimating formation properties, two field examples are presented where air-pressurized slug tests were conducted. The tests were conducted in wells completed in the Madison and Minnelusa aquifers in the Black Hills of South Dakota. The results of these tests also are discussed in Shapiro and Greene (1995).

In the first example, air-pressurized slug tests were conducted in well CQ1 in a high-permeability section of the Minnelusa aquifer in the vicinity of Rapid City, South Dakota. Conducting these tests in a high-permeability zone allowed the pressurized and recovery parts of the tests to be conducted rapidly for the purpose of illustrating the applicability of the method for various termination points in the pressurized part of the test. A hydrogeologic description of the Minnelusa aquifer is given in Greene (1993). The well used for these tests is cased with 16.3-cm-inside-diameter (6.4 inch) steel casing through the upper formations and has a 15.2-cm-diameter (6 inch) open hole in the Minnelusa aquifer. The depth to the top of the open interval, $L_s$, is 41.5 m (136 ft), and the depth to the static-water level, $L_w$, is 16.8 m (55 ft).

Five air-pressurized slug tests were conducted in well CQ1 in the Minnelusa aquifer. In each test, a 103.42 kPa (15 psi) pressure transducer was placed 6.10 m (20 ft) below the static-water level, and an applied air pressure, $p_a$, equal to 34.5 kPa (5 psi) was used, which corresponds to an anticipated maximum water-level change, $\Delta$, equal to 3.51 m (11.53 ft). Each air-pressurized slug test was terminated at a different point during the pressurized part of the test. Tests were conducted where $\Delta_r/\Delta$ was 0.33, 0.50, 0.66, 0.75, and 1.0. The duration of the pressurized part of the slug tests varied from 8 seconds for $\Delta_r/\Delta = 0.33$ to 14 minutes for $\Delta_r/\Delta = 1.0$.

For the test where $\Delta_r/\Delta = 1$, the slug test solution of Cooper and others (1967) was used to interpret the rising water level. The data from the other slug tests, where $\Delta_r/\Delta < 1$, were analyzed using the method developed by Shapiro and Greene (1995) and type curves generated from the program AIRSLUG. The data and type curve matches for these tests are shown in figure 10. For the tests where $\Delta_r/\Delta$ equaled 0.50, 0.66, 0.75, and 1.0, the type curves for $\alpha$ equal to $10^{-4}$ provided the best fit to the data, while the type curve for $\alpha$ equal to $10^{-5}$ provided the best fit to the data from the test where $\Delta_r/\Delta = 0.33$. For all of these tests, the match points on the axes of the type curve and the data curve were the same, $(t - t_r)_m = 32$ seconds for $t_m' = [T(t - t_r)/r_c^2]_m = 1$. Thus, the transmissivity estimated from each test was the same, $2.1 \times 10^{-4}$ $m^2$ /s (195 $ft^2$/day), and did not depend on the point at which the pressurized part of the test was terminated. The storativity was $1.1 \times 10^{-5}$ for the test where $\Delta_r/\Delta = 0.33$, and $1.1 \times 10^{-4}$ for the other air-pressurized slug tests. Reliable estimates of storativity from slug tests are usually not obtained, therefore, a difference of an order of magnitude in the estimated storativity from one test to the next is not unreasonable. The results of the type curve matching for these tests are summarized in table 3.

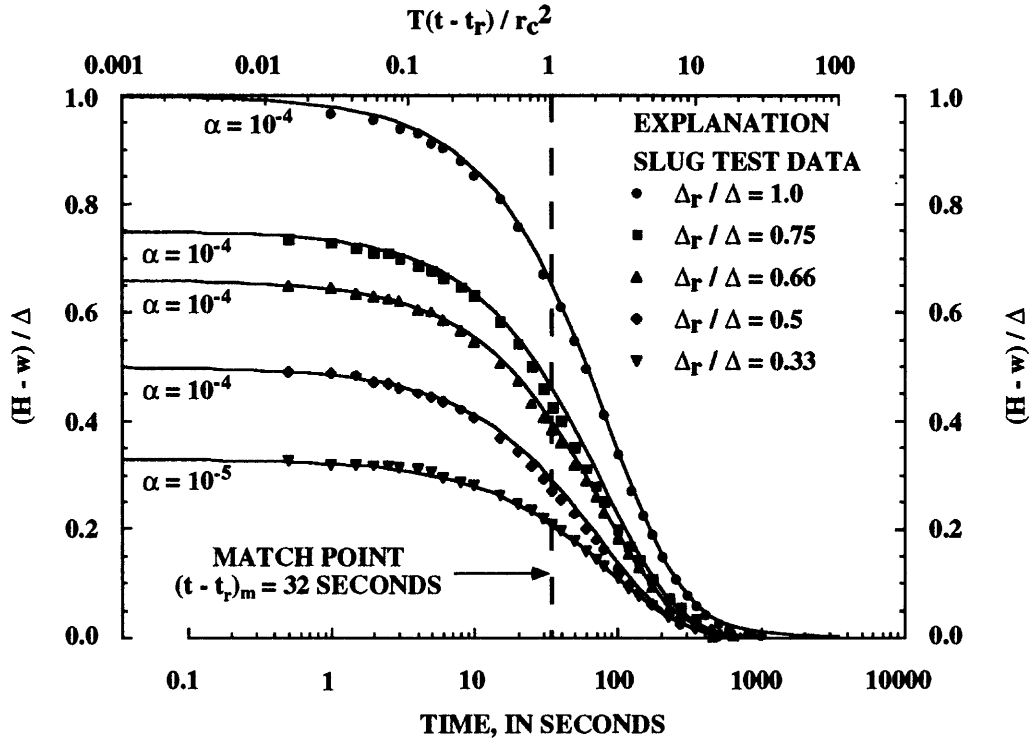


**Figure 10.** Composite plot of type curves and drawdown data from air-pressurized slug tests conducted in well CQ1 in the Minnelusa aquifer near Rapid City, South Dakota.

**Table 3.** Transmissivity and storativity estimates from type-curve matches to drawdown data collected during prematurely terminated air-pressurized slug tests conducted in well CQ1 in the Minnelusa aquifer near Rapid City, South Dakota [Radius of casing, $r_c$ , 8.1 cm (0.27 ft), Radius of open interval, $r_s$, 7.6 cm (0.25 ft)].

| $\frac{\Delta_r}{\Delta}$ | Match Point, $(t - t_r)_m$, in seconds | Match Point, $\frac{T(t - t_r)}{r_c^2} = t_m'$ | $\alpha = \frac{S r_c^2}{r_s^2}$ | Transmissivity, in $m^2/s$ | Transmissivity, in $ft^2/day$ | Storativity |
|---|---|---|---|---|---|---|
| 1.0 | 32 | 1.0 | $10^{-4}$ | $2.1 \times 10^{-4}$ | 195 | $1.1 \times 10^{-4}$ |
| 0.75 | 32 | 1.0 | $10^{-4}$ | $2.1 \times 10^{-4}$ | 195 | $1.1 \times 10^{-4}$ |
| 0.66 | 32 | 1.0 | $10^{-4}$ | $2.1 \times 10^{-4}$ | 195 | $1.1 \times 10^{-4}$ |
| 0.50 | 32 | 1.0 | $10^{-4}$ | $2.1 \times 10^{-4}$ | 195 | $1.1 \times 10^{-4}$ |
| 0.33 | 32 | 1.0 | $10^{-5}$ | $2.1 \times 10^{-4}$ | 195 | $1.1 \times 10^{-5}$ |

The second field example illustrates the savings in time achieved by conducting prematurely terminated air-pressurized slug tests to estimate T and S in low-permeability terranes. Two air-pressurized slug tests were conducted in the Spearfish-East Madison well completed in the Madison aquifer near Spearfish, South Dakota. The hydrogeology of the Madison aquifer is discussed by Greene (1993) and Carter (1994). The Spearfish-East Madison well has a 12.7-cm-inside-diameter (5 inch) steel casing through the upper formations and a 12.1-cm-diameter (4.75 inch) open hole in the Madison aquifer. The data in table 1 discussed in the previous section was obtained from one of the air-pressurized slug tests conducted in the Spearfish-East Madison well. In that test, the column of air in the well was pressurized for 100 minutes and the recovery part of the test took approximately 12 hours for the rising water level to reach the initial static-water level. Thus, the total time to conduct the test required approximately 14 hours, where the pressurized part of the test was prematurely terminated with $\Delta_r/\Delta$ equaled 0.56. The estimates for the transmissivity and storativity were to $9.7 \times 10^{-7}$ $m^2/s$ (0.9 $ft^2/day$) and $1.1 \times 10^{-3}$, respectively, and the type-curve matching for this test is shown in figure 11a. If an air-pressurized slug test was conducted in this well, where the pressurized part of the test was maintained until a new equilibrium-water level was achieved, it would have taken approximately 24 hours to complete the test.

To check the reproducibility of the estimates for T and S in the Spearfish-East Madison well, a second air-pressurized slug test was conducted where the column of air was pressurized for 360 minutes (6 hours) yielding $\Delta_r/\Delta$ equal to 0.87. The recovery part of the test again took approximately 12 hours for the rising water level to reach the initial static-water level. The type-curve matching for this test is shown in figure 11b and the results of the type-curve matching for the two tests are summarized in table 4. Estimates of the transmissivity and storativity from the two tests are the same, however, the second test required approximately 4 hours more to complete than the first test.

**Table 4.** Transmissivity and storativity estimates from type-curve matches to drawdown data collected during prematurely terminated air-pressurized slug tests conducted in the Spearfish-East Madison well near Spearfish, South Dakota. [Radius of casing, $r_c$ , 6.4 cm (0.21 ft), Radius of open interval, $r_s$, 6.0 cm (0.20 ft)].

| $\frac{\Delta_r}{\Delta}$ | Match Point, $(t - t_r)_m$, in minutes | Match Point, $\frac{T(t - t_r)}{r_c^2} = t'_m$ | $\alpha = \frac{S r_c^2}{r_s^2}$ | Transmissivity, in $m^2/s$ | Transmissivity, in $ft^2/day$ | Storativity |
|---|---|---|---|---|---|---|
| 0.56 | 70 | 1.0 | $10^{-3}$ | $9.7 \times 10^{-7}$ | 0.9 | $1.1 \times 10^{-3}$ |
| 0.87 | 70 | 1.0 | $10^{-3}$ | $9.7 \times 10^{-7}$ | 0.9 | $1.1 \times 10^{-3}$ |

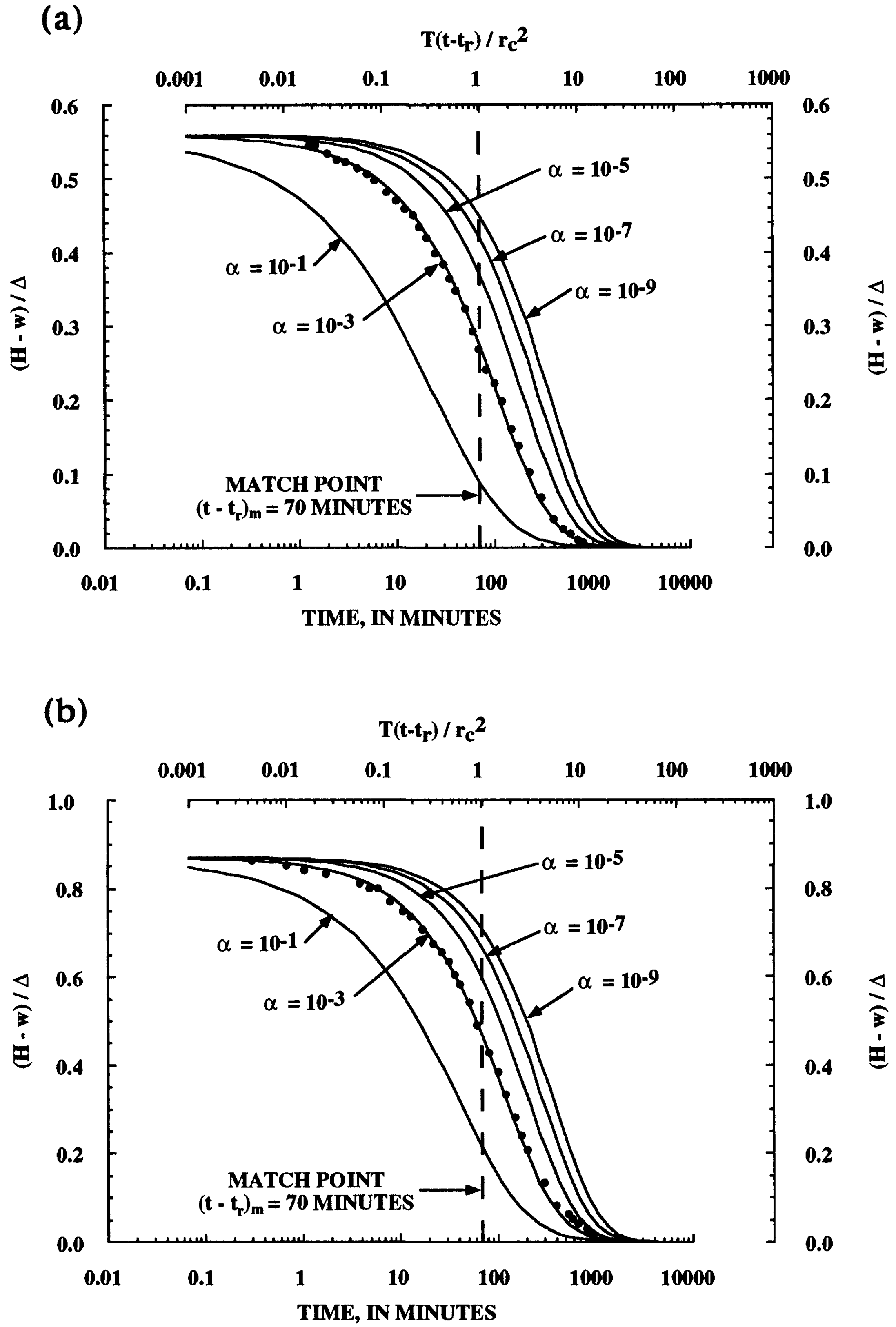


**Figure 11.** Composite plot of type curves and drawdown data from air-pressurized slug tests conducted in the Spearfish-East Madison well near Spearfish, South Dakota, (a) $\Delta_r/\Delta = 0.56$ and (b) $\Delta_r/\Delta = 0.87$.

In principle, the declining water level during the pressurized part of air-pressurized slug tests can be used to estimate transmissivity and storativity. The declining water level is analogous to the slug test solution of Cooper and others (1967). For the tests conducted in the Spearfish-East Madison well, it would have taken approximately 12 hours to reach the new equilibrium-water level using the applied air pressure. However, slight variations in air-pressure at the initial stages of the pressurized part of the test produce pronounced changes in the water level, making it difficult to compare the declining water level and the type curves from the solution of Cooper and others (1967). To illustrate the difficulty that can arise in attempting to estimate formation properties from the declining water level, figure 12 shows the time variation of the air pressure in the casing and the declining water level during the pressurized part of an air-pressurized slug test. The data shown in figure 12 were collected from the first air-pressurized slug test conducted in the Spearfish-East Madison well (table 1).

As long as the fluctuations in the air pressure in the casing during the pressurized part of the test are of a short duration relative to the total time that the well is pressurized, the rising water level during the recovery part of the test can be interpreted using the type curves generated from the solution of Shapiro and Greene (1995). The results from the tests in the Spearfish-East Madison well show that there is a significant savings in time associated with prematurely terminating an air-pressurized slug test to estimate T and S in a low-permeability formation. Furthermore, the declining water level during the pressurized part of the test usually cannot be interpreted because of the variation in air pressure applied to the well casing at the initial stages of the test.

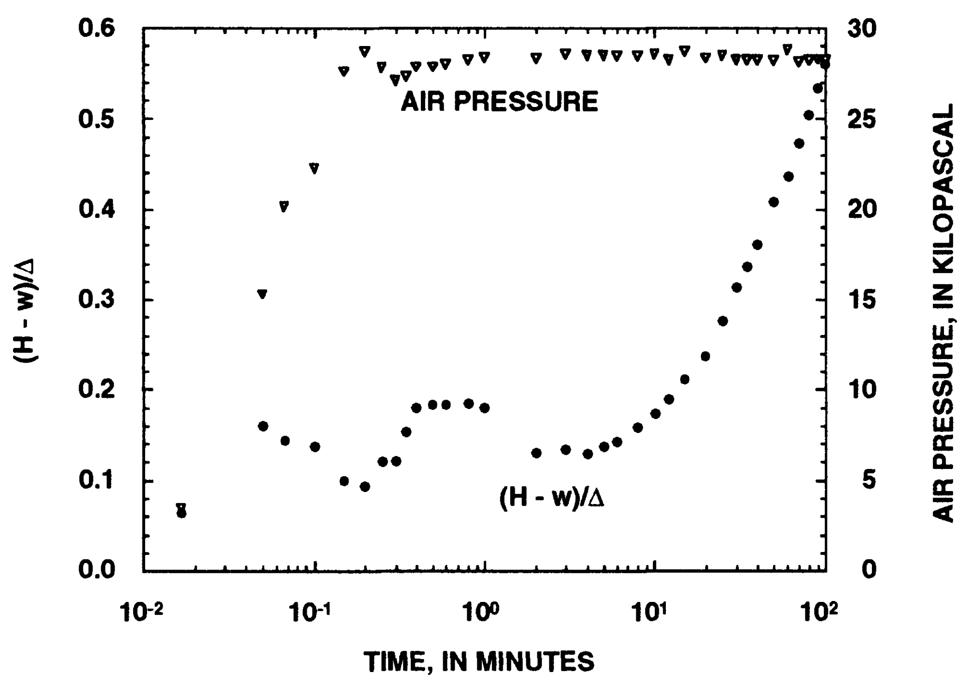


**Figure 12.** Fluctuations in air pressure in the casing and drawdown during the pressurized part of an air-pressurized slug test.

## SUMMARY

Air-pressurized slug tests offer an efficient means of estimating transmissivity and storativity. The test is conducted by pressurizing the air in the casing above the column of water in the well, monitoring the declining water level and then releasing the air pressure and monitoring the rising water level. This test is useful at sites having contaminated formation waters, where disposing of contaminated water and cleaning equipment is a concern. It is also useful in wells having water levels at significant depths below land surface and in large diameter wells where it becomes cumbersome to conduct conventional slug tests by displacing, adding or removing a column of water.

The equipment needed to conduct the air-pressurized slug test is easily constructed and assembled at the top of the well. The equipment consists of an air-tight well-head apparatus that allows the introduction of air to pressurize the well casing and an air-delivery system to maintain a constant air pressure in the well for an extended period of time. Water levels during the test are monitored using a downhole pressure transducer that is fitted through the well-head apparatus using pressure-tight seals. A data logger is used to record the declining and rising water levels during the test.

During the pressurized part of the test, the declining water level can be interpreted using the slug test solution of Cooper and others (1967). However, fluctuations in the applied air pressure during the initial stages of the pressurized part of the test make it difficult to estimate transmissivity and storativity using the type curves of Cooper and others (1967). If a constant air pressure is applied and maintained until a new equilibrium-water level is achieved, and the air pressure in the well then is released instantaneously, the rising water level can be interpreted using the slug test solution of Cooper and others (1967) to estimate transmissivity and storativity.

In low-permeability formations it may take an extended period of time to achieve the equilibrium-water level for the applied air pressure during the pressurized part of the test. However, the total time to conduct an air-pressurized slug test can be reduced, if the pressurized part of the test is terminated prior to achieving the equilibrium-water level. This is referred to as a prematurely terminated air-pressurized slug test. Under these circumstances, the type curves from the solution of Cooper and others (1967) cannot be used to estimate transmissivity and storativity. Instead, transmissivity and storativity are estimated by comparing the recovering water level and type curves generated from the solution of Shapiro and Greene (1995). The Fortran code AIRSLUG, included in this document, is used to generate the type curves to estimate T and S from prematurely terminated air-pressurized slug tests.

# REFERENCES


Carter, J., 1994, Hydrogeology and hydraulic properties of the Madison and Minnelusa aquifers near Spearfish, South Dakota, South Dakota School of Mines and Technology, Masters Thesis, 97 p.

Cooper, H. H., Jr., Bredehoeft, J. D., and Papadopulos, I. S., 1967, Response of a finite-diameter well to an instantaneous charge of water: Water Resources Research, v. 3, no. 1, p. 263-269.

Greene, E. A., 1993, Hydraulic properties of the Madison aquifer system in the western Rapid City Area, South Dakota: US Geological Survey Water-Resources Investigations Report 93-4008, 56 p.

Leap, D. I., 1984, A simple pneumatic device and technique for performing rising water level slug tests: Ground Water Monitoring Review, v. 4, no. 4, p. 141-146.

McLane, G. A., Harrity, D. A. , and Thomsen, K. O., 1991, Slug testing in highly permeable aquifers using a pneumatic method: Hazardous Materials Control, v. 4, no. 3, p. 51-55.

Shapiro, A. M. and Greene, E. A., 1995, Interpretation of prematurely terminated air-pressurized slug tests: Ground Water, v. 33, no. 4, p. 539-546.

# NOMENCLATURE

| | |
|---|---|
| $H$ | initial static-water level |
| $L_w$, | depth to static-water level |
| $L_s$ | depth to top of well screen or open interval of well |
| $p_a$ | pressure applied in well casing |
| $r$ | radial coordinate |
| $r_c$ | radius of well casing |
| $r_s$ | radius of screened (or open) interval of well |
| $S$ | storativity |
| $t$ | time |
| $t_m' = [T(t - t_r)/r_c^2]_m$ | match point on the dimensionless time axis of the type curve corresponding to the match point on the time axis of the data curve, $(t - t_r)_m$ |
| $(t - t_r)_m$ | match point on the time axis of the data curve corresponding to the match point on the dimensionless time axis of the type curve, $t_m' = [T(t - t_r)/r_c^2]_m$ |
| $T(t - t_r)/r_c^2$ | dimensionless time for recovery part of air-pressurized slug test |
| $t_r$ | time at which the recovery part of air-pressurized slug test is initiated |
| $T$ | transmissivity |
| $w$ | water level in casing |
| $(H - w)/\Delta$ | dimensionless drawdown |
| $\alpha$ | $= Sr_s^2/r_c^2$ |
| $\Delta$ | maximum water-level change for the applied air pressure |
| $\Delta_r$ | water-level change at end of pressurized part of air-pressurized slug test ($t = t_r$) |
| $\Delta_r/\Delta$ | fraction of maximum water-level change achieved at the end of the pressurized part of air-pressurized slug test |

# APPENDIX A: MATHEMATICAL MODEL AND SOLUTION

The type curves used to interpret the rising water-level data from air-pressurized slug tests are generated from the solution given by Shapiro and Greene (1995). In their development, the formation is assumed to be homogeneous, isotropic and of infinite areal extent and uniform thickness. Also, the initial hydraulic head in the formation, H, is assumed to be uniform and the screened or open interval of the well is assumed to extend over the entire thickness of the formation.

During an air-pressurized slug test, the water level in the well is defined as

$$w(t) = h(r = r_s, t) - h_a(t) \tag{A.1}$$

where $w(t)$ is the time varying water level in the casing, $h_a(t)$ is the prescribed air pressure (expressed as an equivalent hydraulic head) applied to the water column in the well, $h(r = r_s, t)$ is the time varying hydraulic head in the formation at the well screen, r is the radial coordinate measured at the center of the well, t is time, and $r_s$ is the radius of the well screen or open interval of the well. It is assumed that the air pressure applied to the well will not result in the water level being depressed below the top of the well screen or open interval; therefore, situations where air is forced into the formation are not considered in this analysis. At $t = 0$, $h_a(t)$ is assumed to be at atmospheric pressure and taken to be zero, thus $w(t = 0) = h(r = r_s, t = 0) = H$. For time, $t > 0$, $h_a(t)$ is assumed to be a constant applied air pressure equal to $\Delta$. Here, it is assumed that there is no borehole skin, thus, the hydraulic head in the formation adjacent to the well screen is the same as the hydraulic head in the well at the well screen.

To specify the $w(t)$ in (A.1), the hydraulic head in the formation at the well screen, $h(r = r_s, t)$, must be defined from the equation of fluid mass conservation in the formation and the associated initial and boundary conditions. The equation of fluid mass conservation in the formation is

$$S\frac{\partial h}{\partial t} - T\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial h}{\partial r}\right) = 0 \tag{A.2}$$

where T is transmissivity and S is storativity. This equation is subject to the initial condition

$$h(r, t = 0) = H \tag{A.3}$$

which implies the hydraulic head is uniform in the formation at the start of the test. The boundary conditions associated with (A.2) are

$$-\pi r_c^2 \frac{dw}{dt} + 2\pi r_s T \left.\frac{\partial h}{\partial r}\right|_{r = r_s} = 0 \tag{A.4}$$

$$h(r \to \infty, t) = H \tag{A.5}$$

where $r_c$ is the radius of the well casing. Equation (A.4) states that the change in water level in the well is balanced by the fluid mass entering or leaving the formation at the well screen, while (A.5) states that there is no impact of conducting the test at large distances from the well.

The solution to (A.1)-(A.5) during the pressurized part of the slug test is

$$w'(t') = 1 - F(t') \tag{A.6}$$

where $w' = (H - w)/\Delta$ and $t' = Tt/Sr_s^2$ are the dimensionless drawdown and dimensionless time, respectively, and $F(t')$ is the solution for the water level in a slugged well given by Cooper and others (1967),

$$F(t')=\frac{2}{\pi}\int_0^{\infty} \frac{\exp(-t'u^2)\left\{ J_0(u)\,[u\,Y_0(u) - 2\alpha\,Y_1(u)] - Y_0(u)\,[u\,J_0(u) - 2\alpha\,J_1(u)] \right\}}{[u\,J_0(u) - 2\alpha\,J_1(u)]^2 + [u\,Y_0(u) - 2\alpha\,Y_1(u)]^2}\,du \tag{A.7}$$

where $J_0$ and $J_1$ are the Bessel functions of the first kind and order zero and one, respectively, $Y_0$ and $Y_1$ are the Bessel functions of the second kind of order zero and one, respectively, and $\alpha$ is a dimensionless parameter defining the ratio of storage in the formation per unit volume to the storage in the well per unit volume,

$$\alpha = \frac{r_s^2\,S}{r_c^2} \tag{A.8}$$

Reducing the applied air pressure in the well to atmospheric pressure at $t = t_r$ initiates the recovery part of the slug test. The water level in the casing during the recovery part of the test is given by (Shapiro and Greene, 1995)

$$w'(t') = -F(t') + F(t' - t_r') \tag{A.9}$$

where $t_r' = T\,t_r/S\,r_s^2$.

If variations in the air pressure during the pressurized part of the test are small relative to the magnitude of the applied air pressure and are of short duration relative to the time over which the well is pressurized, equation (A.9) can be used to interpret the recovering water level and estimate formation properties. Under these circumstances, the solution for the recovering water level is insensitive to water level fluctuations during the pressurized part of the test.

# APPENDIX B: AIRSLUG - FORTRAN PROGRAM LISTING

```
C===========================================================================
C     AIRSLUG -- Fortran program to generate type curves to interpret the
C            drawdown data from prematurely terminated air-pressurized
C            slug tests. In the prematurely terminated air-pressurized
C            slug test, the column of air in the well is subject to a
C            constant applied air pressure (pressurized part of test)
C            and then instantaneously reduced to atmospheric pressure
C            (recovery part of test). The drawdown data during the
C            recovery part of the test are interpreted with the type
C            curves generated in this program to estimate transmissivity
C            and storativity.
C
C   Reference:      Shapiro, A. M., and Greene, E. A., 1995, Interpretation
C                   of prematurely terminated air-pressurized slug tests,
C                   Ground Water, v. 33, no. 4, p. 539-546.
C
C                   Greene, E. A., and Shapiro, A. M., 1995, Methods of
C                   conducting air-pressurized slug tests and computation
C                   of type curves for estimating transmissivity and
C                   storativity, U.S. Geological Survey Open-File Report
C                   95-424, 43 p.
C
C                             Prepared by:
C
C                   Allen M. Shapiro and Earl A. Greene
C                          U.S. Geological Survey
C                           431 National Center
C                            Reston, VA 22092
C
C     Subroutine GREEN used for numerical inversion of Laplace
C     transform solution was developed by John Barker (British
C     Geological Survey, written communication, 1986).
C
C===========================================================================
C            EXPLANATION OF INPUT
C===========================================================================
C     DRDELT - fraction of the maximum water-level change for the
C     applied air pressure at end of the pressurized part of
C     the slug test (e.g., DRDELT = 0.8 denotes 80% of the
C     maximum water-level change for the applied air
C     pressure).
C
C     ITYPE  - parameter defining the number of type curves to be
C     generated. (ITYPE = 0, 9 type curves are generated,
C     ITYPE = 1, 1 type curve is generated).
C
C     FILOUT - filename for printing type curve values
```

```
C=========================================================================
C              PROGRAMMING NOTES
C=========================================================================
C       Unit IRS - unit for reading input from the screen
C       Unit IWS - unit for writing to the screen
C       Unit IWF - unit for writing file of type curves
C
C       Units are specified below
C=========================================================================
        IMPLICIT DOUBLE PRECISION (A-H,O-Z)
        COMPLEX*16 FOFS,WORK
        CHARACTER*64 FILOUT
        EXTERNAL FOFS
        COMMON /PARAM/SIG
        COMMON /COM/WORK(8192)
        DIMENSION TYPE(10,150)
C=========================================================================
C              DEFINE UNITS
C=========================================================================
        IRS=5
        IWS=6
        IWF=7
C=========================================================================
C              ENTER INPUT VARIABLES
C=========================================================================
        WRITE (IWS,989)
        WRITE (IWS,990)
        READ (IRS,*) DRDELT
        WRITE (IWS,991)
        READ (IRS,992) FILOUT
        OPEN (UNIT=IWF,FILE=FILOUT,STATUS='UNKNOWN')
        WRITE (IWS,993)
        READ (IRS,*) ITYPE
        IF (ITYPE.EQ.0) THEN
        ITY=9
        ELSE
        ITY=1
        WRITE (IWS,994)
        READ (IRS,*) ALP
        ENDIF
C=========================================================================
        TOLER=1.D-4
        NSIG=6
        EPS=1.D-10
        MMAX=7
C=========================================================================
C              LOOP FOR EACH VALUE OF ALPHA
C=========================================================================
        DO 100 LL=1,ITY
        ALPHA=1.D0/(10.D0**LL)
        F (ITY.EQ.1) ALPHA=ALP
        SIG=1.D0/(2.D0*ALPHA)
        DEL=0.05D0
        NPT=36
```

```
      TDS=-4.D0
      WRITE (IWS,995) LL
C==========================================================================
C             PRESSURIZED PART OF TEST - FIND tr
C==========================================================================
      I=1
   10 TS=10.D0**(TDS+DBLE(I-1)*DEL)
      T=TS*2.D0*SIG
      NFUN=0
      CALL GREEN(FOFT,T,FOFS,NFUN,NSIG,EPS,MMAX,8192,IEND)
      IF (FOFT.LT.(DRDELT-TOLER)) GO TO 15
      IF ((FOFT.GE.(DRDELT-TOLER)).AND.(FOFT.LE.(DRDELT+TOLER)))
     $ GO TO 30
      IF (FOFT.GT.(DRDELT+TOLER)) GO TO 25
   15 CONTINUE
      I=I+1
      GO TO 10
   25 TDE=DLOG10(TS)
      TDS=TDE-DEL
      DEL=(TDE-TDS)/10.D0
      NPT=11
      I=2
      GO TO 10
   30 CONTINUE
      T1=T
C==========================================================================
C             RECOVERY PART OF TEST - GENERATE TYPE CURVE
C==========================================================================
      NPT=101
      DEL=0.05D0
      TDS=-3.D0
      DO 100 I=1,NPT
      TS=10.D0**(TDS+DBLE(I-1)*DEL)
      T=TS*2.D0*SIG
      NFUN=0
      TABS=T1+T
      CALL GREEN(FOFT,TABS,FOFS,NFUN,NSIG,EPS,MMAX,8192,IEND)
      FOFA=FOFT
      NFUN=0
      CALL GREEN(FOFT,T,FOFS,NFUN,NSIG,EPS,MMAX,8192,IEND)
      FOFT=FOFA-FOFT
  100 TYPE(LL+1,I)=FOFT
C
      DO 200 I=1,NPT
  200 TYPE(1,I)=10.D0**(TDS+DBLE(I-1)*DEL)
      DO 210 I=1,NPT
  210 WRITE (IWF,701) (TYPE(LL,I),LL=1,ITY+1)
      WRITE (IWS,996)
C==========================================================================
      CLOSE (UNIT=IWF,STATUS='KEEP')
C==========================================================================
C             FORMAT STATEMENTS
C==========================================================================
  701 FORMAT (1X,1PE12.5,0P9F10.5)
```

```
 989  FORMAT (1X,'AIRSLUG - Program to generate type curves for',
     $1X,'interpreting the',/11X,'drawdown data from prematurely',
     $1X,'terminated air-',
     $/11X,'pressurized slug tests:',
     $//11X,'Reference: Shapiro, A. M., and Greene, E. A., 1995,',
     $/22X,'Interpretation of prematurely terminated air-',
     $/22X,'pressurized slug tests, Ground Water, v. 33, no.',
     $/22X,'4, p. 539-546.')
 990  FORMAT (/1X,'Enter DRDELT - fraction of the maximum water-level',
     $1x,'change for the',
     $/16x,'applied air pressure at end of the pressurized part of',
     $/16x,'the slug test (e.g., DRDELT = 0.8 denotes 80% of the',
     $/16x,'maximum water-level change for the applied air pressure).')
 991  FORMAT (//1X,'Enter FILOUT - filename for printing type curve',
     $1x,'values:')
 992  FORMAT (A)
 993  FORMAT (/1X,'Do you want to generate 9 types curves for 9',
     $1x,'values of alpha',
     $/1X,'= Srs^2/rc^2 = 1.e-1, 1.e-2, 1.e-3, . . . 1.e-9, or',
     $/1X,'1 type curve for a prescribed',
     $1x,'value of alpha?',
     $//1x,'Enter 0 to generate 9 type curves',
     $/1x,'Enter 1 to generate 1 type curve')
 994  FORMAT (/1X,'Enter value of alpha = Srs^2/rc^2')
 995  FORMAT (//1X,'Program is generating type curve',I2)
 996  FORMAT (//1X,'*** Normal Program Termination ***')
C========================================================================
      STOP
      END
C========================================================================
      FUNCTION FOFS(S)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMPLEX*16 FOFS,S,DK0,X,DK1
      COMMON /PARAM/SIG
      X=CDSQRT(S)
      CALL BESS0(DK0,X)
      CALL BESS1(DK1,X)
      FOFS=DK1/((SIG*X*DK0+DK1)*S)
      RETURN
      END
C========================================================================
      SUBROUTINE GREEN(FT,T,FS,NFUN,NSIG,EPS,MMAX,IW,IEND)
C*****************************************************************
C AUTHOR:      JOHN A. BARKER (BRITISH GEOLOGICAL SURVEY)
C VERSION:     2 (NOVEMBER 1986)
C DESCRIPTION: INVERSION OF A LAPLACE TRANSFORM EITHER TO A
C              SPECIFIED NUMBER OF SIGNIFICANT FIGURES OR
C              USING A SPECIFIED NUMBER OF FUNCTION EVALUATIONS
C LANGUAGE:    FORTRAN 77
C*****************************************************************
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMPLEX*16 SUM0,WORK,FS,B,B1,B2,WORK1
      COMMON /COM/WORK(8192)
      PARAMETER (EXAMIN=-180.D0)
```

```
      FT=0.0
      IEND=-1
      IF (T.LT.0.D0) RETURN
C
      IF (NFUN.EQ.0) THEN
      NMAX=2**MMAX
      IEND=3
      IF ((NMAX.LT.8).OR.(NMAX.GT.IW)) RETURN
      ETA=10.D0**(-DBLE(NSIG)-0.301D0)
      KSTEP=1
      RLAM=6.D0/T
      SUM0=201.71439674636756D0*FS(DCMPLX(RLAM,0.D0))
      NFUN=1
      N=4
    1 NM1=N-1
      PIBYN=3.1415926535897932D0/DBLE(N)
      NN=NMAX/N
      DO 2 K=1,NM1,KSTEP
      THETA=DBLE(K)*PIBYN
      IF (K*2.EQ.N) THEN
      ALPHA=0.D0
      ELSE
      ALPHA=THETA/DTAN(THETA)
      ENDIF
      WORK(K*NN)=0.5D0*DEXP(DMAX1(6.D0*ALPHA,EXAMIN))
     $         *DCMPLX(1.D0,THETA+ALPHA*(ALPHA-1.D0)/THETA)
     $         *FS(RLAM*DCMPLX(ALPHA,THETA))
    2 NFUN=NFUN+1
      KSTEP=2
      PSI=6.D0*PIBYN
      CP=2.D0*DCOS(PSI)
      SP=DSIN(PSI)
      B=(0.D0,0.D0)
      B1=B
      DO 3 KA=1,NM1
      K=N-KA
      B2=B1
      B1=B
    3 B=CP*B1-B2+WORK(K*NN)
      FT=RLAM*DREAL(SUM0+CP*B-2.D0*(B1-B*DCMPLX(0.D0,SP)))/N
      IF (N.GT.4) THEN
      DIF=DABS(FT-FTOLD)
      IEND=1
      IF (DMAX1(DIF,DABS(FT),DABS(FTOLD)).LT.EPS) RETURN
      IEND=0
      IF (DIF/DMAX1(DABS(FT),EPS).LT.ETA) RETURN
      IEND=2
      IF (N.EQ.NMAX) RETURN
      ENDIF
      FTOLD=FT
      N=N+N
      GO TO 1
C
      ELSEIF(NFUN.GT.0) THEN
```

```
C
      RLAM=6.D0/T
      SUM0=201.71439674636756D0*FS(DCMPLX(RLAM,0.D0))
      NM1=NFUN-1
      PIBYN=3.1415926535897932D0/NFUN
      PSI=6.D0*PIBYN
      CP=2.D0*DCOS(PSI)
      SP=DSIN(PSI)
      B=(0.D0,0.D0)
      B1=B
      DO 4 KA=1,NM1
      K=NFUN-KA
      THETA=K*PIBYN
      IF (K*2.EQ.NFUN) THEN
      ALPHA=0.0
      ELSE
      ALPHA=THETA/DTAN(THETA)
      ENDIF
      WORK1=0.5D0*DEXP(DMAX1(6.D0*ALPHA,EXAMIN))
     $     *DCMPLX(1.D0,THETA+ALPHA*(ALPHA-1.D0)/THETA)
     $     *FS(RLAM*DCMPLX(ALPHA,THETA))
      B2=B1
      B1=B
    4 B=CP*B1-B2+WORK1
      FT=RLAM*DREAL(SUM0+CP*B-2.D0*(B1-B*DCMPLX(0.D0,SP)))/NFUN
      IEND=0
C
      ELSE
C
      IEND=4
C
      ENDIF
C
      RETURN
      END
C     ===========================================================
      SUBROUTINE BESS0(DK0,Z)
C     ===========================================================
C             Subroutine to evaluate Bessel function K0
C     ===========================================================
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMPLEX*16 DK0,Z,DI0,X,Y
C
      EU=0.577215664901532860606512D0
      PI=3.141592653589793238462643D0
C
      EPS=1.D-10
      NSIG=6
      ETA=10.D0**(-DBLE(NSIG)-0.301D0)
C
      IF(CDABS(Z).GT.7.5D0) GO TO 100
C
C FOR /Z/ < 7.5
C
```

```
      X=0.25D0*Z*Z
C
C GENERATE DI0
      DI0=DCMPLX(1.D0,0.D0)
      I=0
      DNOM=1.D0
  10  I=I+1
      DNOM=DNOM*I
      DI0=DI0+(X**I)/(DNOM*DNOM)
      IF(I.LT.6) GO TO 30
      IF(I.EQ.20) GO TO 40
      DIF=DABS(DREAL(DI0)-DROLD)
      IF(DMAX1(DIF,DABS(DREAL(DI0)),DABS(DROLD)).LT.EPS) GO TO 20
      IF(DIF/DMAX1(DABS(DREAL(DI0)),EPS).LT.ETA) GO TO 20
      GO TO 30
  20  DIF=DABS(DIMAG(DI0)-DIOLD)
      IF(DMAX1(DIF,DABS(DIMAG(DI0)),DABS(DIOLD)).LT.EPS) GO TO 40
      IF(DIF/DMAX1(DABS(DIMAG(DI0)),EPS).LT.ETA) GO TO 40
  30  DROLD=DREAL(DI0)
      DIOLD=DIMAG(DI0)
      GO TO 10
  40  CONTINUE
C
C GENERATE DK0
      DK0=-1.D0*(CDLOG(0.5D0*Z)+EU)*DI0
      I=0
      DNOM=1.D0
      COEF=0.D0
  50  I=I+1
      DNOM=DNOM*I
      COEF=COEF+1.D0/DBLE(I)
      DK0=DK0+COEF*(X**I)/(DNOM*DNOM)
      IF(I.LT.6) GO TO 70
      IF(I.EQ.20) RETURN
      DIF=DABS(DREAL(DK0)-DROLD)
      IF(DMAX1(DIF,DABS(DREAL(DK0)),DABS(DROLD)).LT.EPS) GO TO 60
      IF(DIF/DMAX1(DABS(DREAL(DK0)),EPS).LT.ETA) GO TO 60
      GO TO 70
  60  DIF=DABS(DIMAG(DK0)-DIOLD)
      IF(DMAX1(DIF,DABS(DIMAG(DK0)),DABS(DIOLD)).LT.EPS) RETURN
      IF(DIF/DMAX1(DABS(DIMAG(DK0)),EPS).LT.ETA) RETURN
  70  DROLD=DREAL(DK0)
      DIOLD=DIMAG(DK0)
      GO TO 50
C
C FOR /Z/ > 7.5
C
 100  Y=CDEXP(-Z)*DSQRT(PI/2.D0)/CDSQRT(Z)
      DK0=Y
      I=0
      DNOM=1.D0
      DNUM=1.D0
 110  I=I+1
      K=2*I-1
```

```
      DNOM=DNOM*I
      DNUM=-1.D0*K*K*DNUM
      DK0=DK0+Y*DNUM/(DNOM*(8.D0*Z)**I)
      IF(I.LT.3) GO TO 130
      IF(I.EQ.20) RETURN
      DIF=DABS(DREAL(DK0)-DROLD)
      IF(DMAX1(DIF,DABS(DREAL(DK0)),DABS(DROLD)).LT.EPS) GO TO 120
      IF(DIF/DMAX1(DABS(DREAL(DK0)),EPS).LT.ETA) GO TO 120
      GO TO 130
  120 DIF=DABS(DIMAG(DK0)-DIOLD)
      IF(DMAX1(DIF,DABS(DIMAG(DK0)),DABS(DIOLD)).LT.EPS) RETURN
      IF(DIF/DMAX1(DABS(DIMAG(DK0)),EPS).LT.ETA) RETURN
  130 DROLD=DREAL(DK0)
      DIOLD=DIMAG(DK0)
      GO TO 110
      END
C     ==================================================================
      SUBROUTINE BESS1(DK1,Z)
C     ==================================================================
C              Subroutine to evaluate Bessel function K1
C     ==================================================================
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMPLEX*16 DK1,Z,DI1,X,Y
      EU=0.5772156649015328606065 12D0
      PI=3.14159265358979323846264 3D0
C
      EPS=1.D-10
      NSIG=6
      ETA=10.D0**(-DBLE(NSIG)-0.301D0)
C
      IF(CDABS(Z).GT.7.5D0) GO TO 100
C
C FOR /Z/ < 7.5
C
      X=0.25D0*Z*Z
C
C GENERATE DI1
      Y=0.5D0*Z
      DI1=Y
      I=0
      DNOM1=1.D0
      DNOM2=1.D0
   10 I=I+1
      DNOM1=DNOM1*I
      DNOM2=DNOM2*(I+1)
      DI1=DI1+Y*(X**I)/(DNOM1*DNOM2)
      IF(I.LT.6) GO TO 30
      IF(I.EQ.20) GO TO 40
      DIF=DABS(DREAL(DI1)-DROLD)
      IF(DMAX1(DIF,DABS(DREAL(DI1)),DABS(DROLD)).LT.EPS) GO TO 20
      IF(DIF/DMAX1(DABS(DREAL(DI1)),EPS).LT.ETA) GO TO 20
      GO TO 30
   20 DIF=DABS(DIMAG(DI1)-DIOLD)
      IF(DMAX1(DIF,DABS(DIMAG(DI1)),DABS(DIOLD)).LT.EPS) GO TO 40
```

```
      IF(DIF/DMAX1(DABS(DIMAG(DI1)),EPS).LT.ETA) GO TO 40
 30   DROLD=DREAL(DI1)
      DIOLD=DIMAG(DI1)
      GO TO 10
 40   CONTINUE
C
C GENERATE DK1
      DK1=(1.D0/Z)+CDLOG(0.5D0*Z)*DI1
      Y=-0.25D0*Z
      DK1=DK1+Y*(-EU-EU+1.D0)
      I=0
      DNUM1=-EU
      DNUM2=-EU+1.D0
      DNOM1=1.D0
      DNOM2=1.D0
 50   I=I+1
      DNUM1=DNUM1+1.D0/DBLE(I)
      DNUM2=DNUM2+1.D0/DBLE(I+1)
      DNOM1=DNOM1*I
      DNOM2=DNOM2*(I+1)
      DK1=DK1+Y*(DNUM1+DNUM2)*(X**I)/(DNOM1*DNOM2)
      IF(I.LT.6) GO TO 70
      IF(I.EQ.20) RETURN
      DIF=DABS(DREAL(DK1)-DROLD)
      IF(DMAX1(DIF,DABS(DREAL(DK1)),DABS(DROLD)).LT.EPS) GO TO 60
      IF(DIF/DMAX1(DABS(DREAL(DK1)),EPS).LT.ETA) GO TO 60
   GO  TO 70
 60   DIF=DABS(DIMAG(DK1)-DIOLD)
      IF(DMAX1(DIF,DABS(DIMAG(DK1)),DABS(DIOLD)).LT.EPS) RETURN
      IF(DIF/DMAX1(DABS(DIMAG(DK1)),EPS).LT.ETA) RETURN
 70   DROLD=DREAL(DK1)
      DIOLD=DIMAG(DK1)
      GO TO 50
C
C FOR /Z/ > 7.5
C
 100  Y=CDEXP(-Z)*DSQRT(PI/2.D0)/CDSQRT(Z)
      DK1=Y
      I=0
      DNOM=1.D0
      DNUM=1.D0
 110  I=I+1
      K=2*I-1
      DNOM=DNOM*I
      DNUM=(4-K*K)*DNUM
      DK1=DK1+Y*DNUM/(DNOM*(8.D0*Z)**I)
      IF(I.LT.3) GO TO 130
      IF(I.EQ.20) RETURN
      DIF=DABS(DREAL(DK1)-DROLD)
      IF(DMAX1(DIF,DABS(DREAL(DK1)),DABS(DROLD)).LT.EPS) GO TO 120
      IF(DIF/DMAX1(DABS(DREAL(DK1)),EPS).LT.ETA) GO TO 120
      GO TO 130
 120  DIF=DABS(DIMAG(DK1)-DIOLD)
      IF(DMAX1(DIF,DABS(DIMAG(DK1)),DABS(DIOLD)).LT.EPS) RETURN
```

```
      IF(DIF/DMAX1(DABS(DIMAG(DK1)),EPS).LT.ETA) RETURN
130   DROLD=DREAL(DK1)
      DIOLD=DIMAG(DK1)
      GO TO 110
      END
```