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# Standard Test Method for Determining Transmissivity and Storativity of Low Permeability Rocks by In Situ Measurements Using Pressure Pulse Technique[1]

This standard is issued under the fixed designation D4631; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This test method covers a field procedure for determining the transmissivity and storativity of geological formations having permeabilities lower than $10^{-3}$ μm$^2$ (1 millidarcy) using the pressure pulse technique.

1.2 The transmissivity and storativity values determined by this test method provide a good approximation of the capacity of the zone of interest to transmit water, if the test intervals are representative of the entire zone and the surrounding rock is fully water saturated.

1.3 The values stated in SI units are to be regarded as the standard. The values in parentheses are for information only.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Terminology

2.1 *Definitions of Terms Specific to This Standard:*

2.1.1 *transmissivity, T*—the transmissivity of a formation of thickness, *b*, is defined as follows:

$$T = K \cdot b \tag{1}$$

*where:*

$K$ = equivalent formation hydraulic conductivity (efhc).

The efhc is the hydraulic conductivity of a material if it were homogeneous and porous over the entire interval. The hydraulic conductivity, *K*, is related to the equivalent formation, *k*, as follows:

$$K = k\rho g/\mu \tag{2}$$

*where:*

$\rho$ = fluid density,
$\mu$ = fluid viscosity, and
$g$ = acceleration due to gravity.

2.1.2 *storativity, S*—the storativity (or storage coefficient) of a formation of thickness, *b* , is defined as follows:

$$S = S_s \cdot b \tag{3}$$

*where:*

$S_s$ = equivalent bulk rock specific storage (ebrss).

The ebrss is defined as the specific storage of a material if it were homogeneous and porous over the entire interval. The specific storage is given as follows:

$$S_s = \rho g\left(C_b + nC_w\right) \tag{4}$$

*where:*

$C_b$ = bulk rock compressibility,
$C_w$ = fluid compressibility, and
$n$ = formation porosity.

2.2 *Symbols:*

2.2.1 $C_b$—bulk rock compressibility [$M^{-1}LT^2$].

2.2.2 $C_w$—compressibility of water [$M^{-1}LT^2$].

2.2.3 $K$—hydraulic conductivity [$LT^{-1}$].

2.2.3.1 *Discussion*—The use of the symbol *K* for the term hydraulic conductivity is the predominant usage in groundwater literature by hydrogeolists, whereas the symbol *k* is commonly used for this term in rock mechanics and soil science.

2.2.4 $L$—length of packed-off zone [$L$].

2.2.5 $P$—excess test hole pressure [$ML^{-1}T^{-2}$].

2.2.6 $P_o$—initial pressure pulse [$ML^{-1}T^{-2}$].

2.2.7 $S$—storativity (or storage coefficient) (dimensionless).

2.2.8 $S_s$—specific storage [$L^{-1}$].

2.2.9 $T$—transmissivity [$L^2T^{-1}$].

2.2.10 $V_w$—volume of water pulsed [$L^3$].

2.2.11 $b$—formation thickness [$L$].

2.2.12 $e$—fracture aperture [$L$].

2.2.13 $g$—acceleration due to gravity [$LT^{-2}$].

2.2.14 $k$—permeability [$L^2$].

[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Groundwater and Vadose Zone Investigations.

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2.2.15 $n$—porosity (dimensionless).

2.2.16 $r_w$—radius of test hole [$L$].

2.2.17 $t$—time elapsed from pulse initiation [$T$].

2.2.18 α—dimensionless parameter.

2.2.19 β—dimensionless parameter.

2.2.20 μ—viscosity of water [$ML^{-1}T^{-1}$].

2.2.21 ρ—density of water [ $ML^{-3}$].

## 3. Summary of Test Method

3.1 A borehole is first drilled into the rock mass, intersecting the geological formations for which the transmissivity and storativity are desired. The borehole is cored through potential zones of interest, and is later subjected to geophysical borehole logging over these intervals. During the test, each interval of interest is packed off at top and bottom with inflatable rubber packers attached to high-pressure steel tubing. After inflating the packers, the tubing string is completely filled with water.

3.2 The test itself involves applying a pressure pulse to the water in the packed-off interval and tubing string, and recording the resulting pressure transient. A pressure transducer, located either in the packed-off zone or in the tubing at the surface, measures the transient as a function of time. The decay characteristics of the pressure pulse are dependent on the transmissivity and storativity of the rock surrounding the interval being pulsed and on the volume of water being pulsed. Alternatively, under non-artesian conditions, the pulse test may be performed by releasing the pressure on a shut-in well, thereby subjecting the well to a negative pressure pulse. Interpretation of this test method is similar to that described for the positive pressure pulse.

## 4. Significance and Use

4.1 *Test Method*—The pulse test method is used to determine the transmissivity and storativity of low-permeability formations surrounding the packed-off intervals. This test method is considerably shorter in duration than the pump and slug tests used in more permeable rocks. To obtain results to the desired accuracy, pump and slug tests in low-permeability formations are too time consuming, as indicated in Fig. 1 (from Bredehoeft and Papadopulos (**1**)).[2]

4.2 *Analysis*—The transient pressure data obtained using the suggested method are evaluated by the curve-matching technique described by Bredehoeft and Papadopulos (**1**), or by an analytical technique proposed by Wang et al (**2**). The latter is particularly useful for interpreting pulse tests when only the early-time transient pressure decay data are available.

4.3 *Units:*

4.3.1 *Conversions*—The permeability of a formation is often expressed in terms of the unit darcy. A porous medium has a permeability of 1 darcy when a fluid of viscosity 1 cP (1 mPa·s) flows through it at a rate of 1 $cm^3$/s ($10^{-6}$ $m^3$/s)/1 $cm^2$ ($10^{-4}$ $m^2$) cross-sectional area at a pressure differential of 1 atm (101.4 kPa)/1 cm (10 mm) of length. One darcy corresponds to 0.987 $μm^2$. For water as the flowing fluid at 20°C, a hydraulic conductivity of 9.66 μm/s corresponds to a permeability of 1 darcy.

4.3.2 *Viscosity of Water*—Table 1 shows the viscosity of water as a function of temperature.

## 5. Apparatus

NOTE 1—A schematic of the test equipment is shown in Fig. 2.

5.1 *Source of Pressure Pulse*—A pump or pressure intensifier shall be capable of injecting an additional amount of water to the water-filled tubing string and packed-off test interval to produce a sharp pressure pulse of up to 1 MPa (145 psi) in magnitude, preferably with a rise time of less than 1 % of one half of the pressure decay ($P/P_o$ = 0.5).

5.2 *Packers*—Hydraulically actuated packers are recommended because they produce a positive seal on the borehole wall and because of the low compressibility of water they are also comparatively rigid. Each packer shall seal a portion of the borehole wall at least 0.5 m in length, with an applied pressure at least equal to the excess maximum pulse pressure to be

[2] The boldface numbers in parentheses refer to a list of references at the end of this standard.



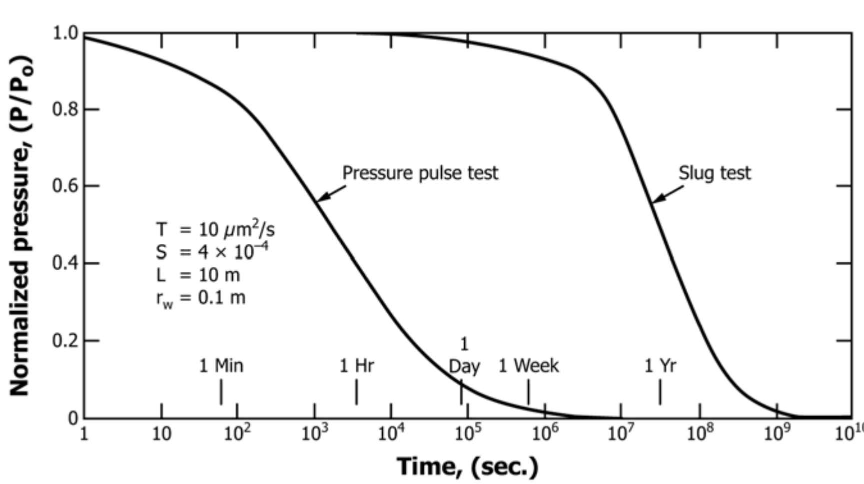


**FIG. 1 Comparative Times for Pressure Pulse and Slug Tests**

**TABLE 1 Viscosity of Water as a Function of Temperature**

| Temperature, °C | Absolute Viscosity, mPa·s |
|---|---|
| 0 | 1.79 |
| 2 | 1.67 |
| 4 | 1.57 |
| 6 | 1.47 |
| 8 | 1.39 |
| 10 | 1.31 |
| 12 | 1.24 |
| 14 | 1.17 |
| 16 | 1.11 |
| 18 | 1.06 |
| 20 | 1.00 |
| 22 | 0.96 |
| 24 | 0.91 |
| 26 | 0.87 |
| 28 | 0.84 |
| 30 | 0.80 |
| 32 | 0.77 |
| 34 | 0.74 |
| 36 | 0.71 |
| 38 | 0.68 |
| 40 | 0.66 |

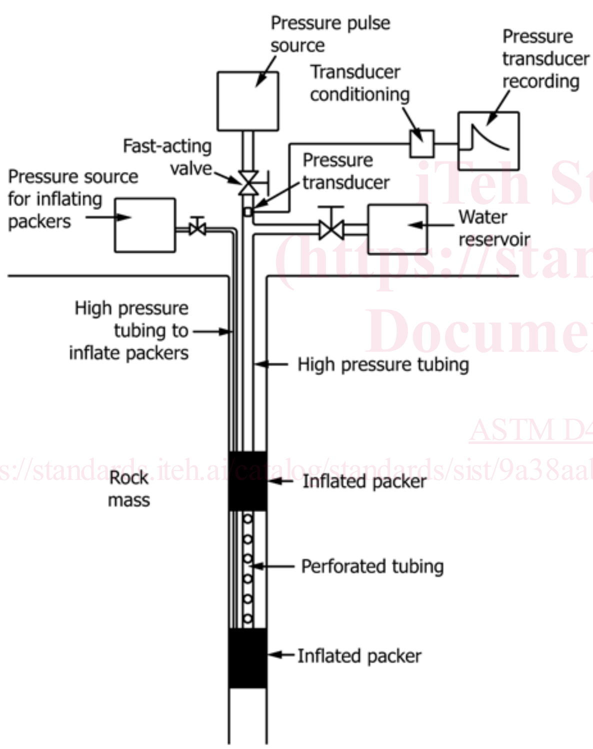


**FIG. 2 Schematic of Test Equipment**

applied to the packed-off interval and less than the formation fracture pressure at that depth.

5.3 *Pressure Transducers*—The test pressure may be measured directly in the packed-off test interval or between the fast-acting valve and the test interval with an electronic pressure transducer. In either case the pressure shall be recorded at the surface as a function of time. The pressure transducer shall have an accuracy of at least ±3 kPa (±0.4 psi), including errors introduced by the recording system, and a resolution of at least 1 kPa (0.15 psi).

5.4 *Hydraulic Systems*—The inflatable rubber packers shall be attached to high-pressure steel tubing reaching to the surface. The packers themselves shall be inflated with water using a separate hydraulic system. The pump or pressure intensifier providing the pressure pulse shall be attached to the steel tubing at the surface. If the pump is used, a fast-operating valve shall be located above, but as near as practical to the upper packer. That valve should be located less than 10 m above the anticipated equilibrium head in the interval being tested to avoid conditions in the tubing changing during the test from a full water column to a falling water-level column because of formation of a free surface at or near zero absolute pressure (Neuzil (**3**)).

## 6. Procedure

6.1 *Drilling Test Holes:*

6.1.1 *Number and Orientation*—The number of test holes shall be sufficient to supply the detail required by the scope of the project. The test holes shall be directed to intersect major fracture sets, preferable at right angles.

6.1.2 *Test Hole Quality*—The drilling procedure shall provide a borehole sufficiently smooth for packer seating, shall contain no rapid changes in direction, and shall minimize formation damage.

6.1.3 *Test Holes Cored*—Core the test holes through zones of potential interest to provide information for locating test intervals.

6.1.4 *Core Description*—Describe the rock core from the test holes with particular emphasis on the lithology and natural discontinuities.

6.1.5 *Geophysical Borehole Logging*—Log geophysically the zones of potential interest. In particular, run electrical-induction and gamma-gamma density logs. Run other logs as required.

6.1.6 *Washing Test Holes*—The test holes must not contain any material that could be washed into the permeable zones during testing, thereby changing the transmissivity and storativity. Flush the test holes with clean water until the return is free from cuttings and other dispersed solids.

6.2 *Test Intervals:*

6.2.1 *Selection of Test Intervals*—Test intervals are determined from the core descriptions, geophysical borehole logs, and, if necessary, from visual inspection of the borehole with a borescope or television camera.

6.2.2 *Changes in Lithology*—Test each major change in lithology that can be isolated between packers.

6.2.3 *Sampling Discontinuities*—Discontinuities are often the major permeable features in hard rock. Test jointed zones, fault zones, bedding planes, and the like, both by isolating individual features and by evaluating the combined effects of several features.

6.2.4 *Redundancy of Tests*—To evaluate variability in transmissivity and storativity, conduct several tests in each rock type, if homogeneous. If the rock is not homogeneous, each set of tests should encompass similar types of discontinuities.

6.3 *Test Water:*

6.3.1 *Quality*—Water used for pressure pulse tests shall be clean and compatible with the formation. Even small amounts of dispersed solids in the injection water could plug the rock face of the test interval and result in a measured transmissivity value that is erroneously low.

6.3.2 *Temperature*—The lower limit of the test water temperature shall be 5°C below that of the rock mass to be tested. Cold water injected into a warm rock mass causes air to come out of solution, and the resulting bubbles will radically modify the pressure transient characteristics.

6.4 *Testing:*

6.4.1 *Filling and Purging System*—Allow sufficient time after washing the test hole for any induced formation pressures to dissipate. Once the packers have been set, slowly fill the tubing string and packed-off interval with water to ensure that no air bubbles will be trapped in the test interval and tubing.

6.4.2 *Pressure Pulse Test*—This range of pressures is in most cases sufficiently low to minimize distortion of fractures adjacent to the test hole, but in no case should the pressure exceed the minimum principal ground stress. Record the resulting pressure pulse and decay transient detected by the pressure transducer as a function of time. A typical record is shown in Fig. 3.

6.4.2.1 Before the pressure pulse test can be started it is necessary to reliably estimate the natural pressure in the test interval. See 7.1.1 and Fig. 3 for a description of a method to prepare the system for the pulse test. After the pressure is at, or estimated to be approaching at a predictable rate, near-equilibrium conditions, then rapidly pressurize the tubing, typically to between 300 and 600 kPa (50 to 100 psi), and then shut in.

## 7. Calculation and Interpretation of Test Data

7.1 The type of matching technique developed by Bredehoeft and Papadopulos (**1**) involves plotting normalized pressure (the ratio of the excess borehole pressure, $P$, at a given time to the initial pressure pulse, $P_o$) against the logarithm of time, as indicated in Fig. 1 and Fig. 3. The pulse decay is given as follows:

$$\frac{P}{P_o} = F(\alpha,\beta) \tag{5}$$

*where:*

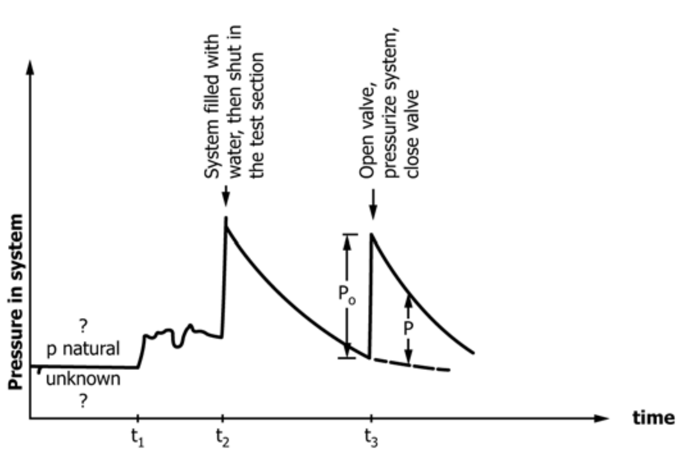


**FIG. 3 Typical Pressure Record**

$\alpha$ and $\beta$ = dimensionless parameters given by: to:

$$\alpha = \pi r^2_w S / V_w C_w \rho g \tag{6}$$

$$\beta = \pi T t / V_w C_w \rho g \tag{7}$$

and:

*where:*

$V_w$ = volume of water being pulsed,
$r_w$ = well radius,
$t$ = time elapsed from pulse initiation,
$C_w$ = compressibility of water,
$T$ = transmissivity,
$S$ = storage coefficient,
$\rho$ = density of water, and
$g$ = gravitational acceleration.

Tables of the function $F(\alpha\ \beta)$ have been provided by Cooper, et al (**4**), Papadopulos (**5**), and Bredehoeft and Papadopulos (**1**).

7.1.1 In Fig. 3 the pressure, $p$, shown before (to the left of) Time $t_1$ represents the unknown natural pressure in the interval eventually to be tested. The drill hole encounters that interval at Time $t_1$ and from then until Time $t_2$ the pressure variation reflects the effects of drilling and test hole development. If the interval consists of rocks or sediments of low hydraulic conductivity, there might be a long time period before the water level in an open hole would stabilize to the equilibrium level. For that reason before a pulse test can be conducted we want to establish a condition that provides a reasonable estimate of the undisturbed pressure for the interval. The following procedure is intended to provide that condition. At Time $t_2$ the packers are inflated, and then the system is filled with water and shut in. By this operation the change in pressure in the packed-off interval will reflect a compressive system and should approach the pressure in the interval being tested much more rapidly than would the water level in an open test hole. Monitoring the pressure changes should indicate when near-equilibrium conditions are approached. At Time $t_3$ the value is opened, the system is subjected to the Pulse $P_o$, and the valve is closed. Monitoring the heads after Time $t_3$ gives the data needed to use the calculation procedure of Bredehoeft and Papadopulos.

7.1.1.1 Neuzil (**3**) points out the necessity of measuring the amount of water used to create the pulse to account for the fact that the compressibility of the shut-in test system can be larger than $C_w$ , the compressibility of water. Neuzil (**3**) suggests that the larger compressibility reflects "give" in the downhole test equipment and in the tubing, and possibly air trapped in the system. The direct computation of the observed test system compressibility can be expressed as

$$C_{obs} = \frac{dv/v}{dp} \tag{8}$$

*where:*

$v$ = total fluid volume of the test system,
$dv$ = injected volume (the pulse), and
$dp$ = pressure pulse.

7.2 The method for analyzing pulse decay data depends on whether the parameter, $\alpha$, is larger or smaller than 0.1. Since