INTERNATIONAL

Designation: D4631 – 18

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 *Units*—The values stated in SI units are to be regarded as the standard. The values in parentheses are mathematical conversions provided for information only and are not considered standard. Reporting of test results in units other than SI shall not be regarded as nonconformance with this standard.

1.4 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026, unless superseded by this standard.

1.4.1 For purposes of comparing a measured or calculated value(s) with specified limits, the measured or calculated value(s) shall be rounded to the nearest decimal or significant digits in the specified limits.

1.4.2 The procedures used to specify how data are collected/recorded or calculated in this standard are regarded as the industry standard. In addition, they are representative of the significant digits that generally should be retained. The procedures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; and it is common practice to increase or reduce significant digits of reported data to be commensurate with these conditions. It is beyond the scope of this standard to consider significant digits used in analysis methods for engineering design.

1.5 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D2113 Practice for Rock Core Drilling and Sampling of Rock for Site Exploration

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D5717 Guide for Design of Ground-Water Monitoring Systems in Karst and Fractured-Rock Aquifers (Withdrawn 2005)[3]

D6026 Practice for Using Significant Digits in Geotechnical Data

F2070 Specification for Transducers, Pressure and Differential, Pressure, Electrical and Fiber-Optic

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of common technical terms in this standard, refer to Terminology D653.

3.2 *Symbols:*

[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] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

***A Summary of Changes section appears at the end of this standard**

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

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

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

3.2.3.1 *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.

3.2.4 L—length of packed-off zone [L].

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

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

3.2.7 S—storativity (or storage coefficient) (dimensionless).

3.2.8 S_s—specific storage [L^{-1}].

3.2.9 T—transmissivity [L^2T^{-1}].

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

3.2.11 b—formation thickness [L].

3.2.12 e—fracture aperture [L].

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

3.2.14 k—permeability [L^2].

3.2.15 n—porosity (dimensionless).

3.2.16 r_w—radius of test hole [L].

3.2.17 t—time elapsed from pulse initiation [T].

3.2.18 α—dimensionless parameter.

3.2.19 β—dimensionless parameter.

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

3.2.21 ρ—density of water [ML^{-3}].

4. Summary of Test Method

4.1 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 filled with water.

4.2 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, measuring 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-confining conditions, the pulse test may be performed imposing a pressure pulse and then releasing the pressure on a shut-in well, thereby subjecting the well to a negative pressure pulse. Interpretation of this test method is like that described for the positive pressure pulse.

5. Significance and Use

5.1 *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 pumping and slug tests used in more permeable rocks. To obtain results to the desired accuracy, pumping and slug tests in low-permeability formations are too time consuming, as indicated in Fig. 1 (from Bredehoeft and Papadopulos (**1**)).[4]

5.2 *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:

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

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

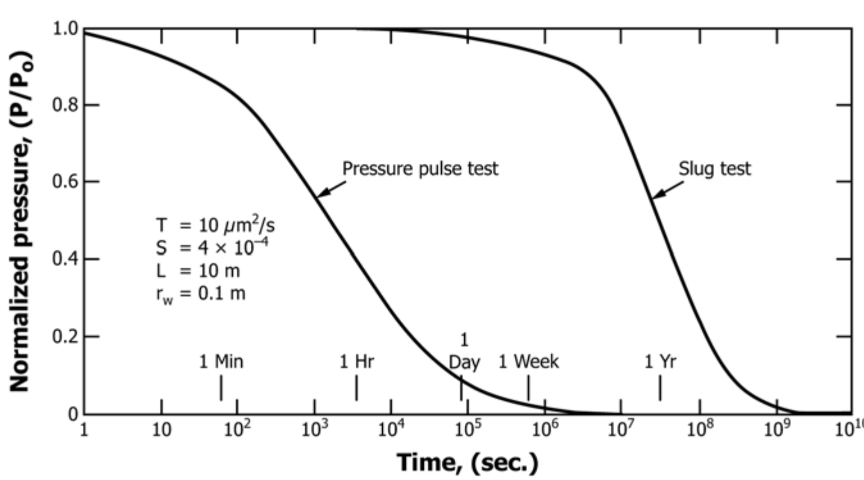

FIG. 1 Comparative Times for Pressure Pulse and Slug Tests

where:

ρ = fluid density,
μ = fluid viscosity, and
g = acceleration due to gravity.

5.3 *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.

5.4 *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.

5.5 *Units:*

5.5.1 *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.

NOTE 1—A darcy (or darcy unit) and millidarcy (md or mD) are units of permeability. They are not SI units, but are widely used in petroleum engineering and geology. A darcy has dimensional units in length.

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

NOTE 2—The quality of the result produced by this standard is dependent on the competence of the personnel performing it and the suitability of the equipment and facility used. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing/sampling/observation/ and the like. Users of this standard are cautioned that compliance with Practice D3740 does not itself guarantee reliable results. Reliable results depend on many factors; D3740 provides a means of evaluating some of those factors.

NOTE 3—The function of wells in any unconfined setting in a fractured terrain might make the determination of k problematic because the wells might only intersect tributary or subsidiary channels or conduits. The problems determining the k of a channel or conduit notwithstanding, the partial penetration of tributary channels may make determination of a meaningful number difficult. If plots of k in carbonates and other fractured settings are made and compared, they may show no indication that there are conduits or channels present, except when with the lowest probability one maybe intersected by a borehole and can be verified, such problems are described by Worthington (**3**) Smart, 1999 (**4**). Additional guidance can be found in D5717.

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

6. Calibration, Verification, Functional Checks

6.1 Prior to use, the test equipment will be verified for operation, freedom from leakage and data recording.

6.2 Pressure transducers will be checked for operation and verified against known devices or calibrated using known standards (F2070).

7. Apparatus

NOTE 4—A schematic of the test equipment is shown in Fig. 2.

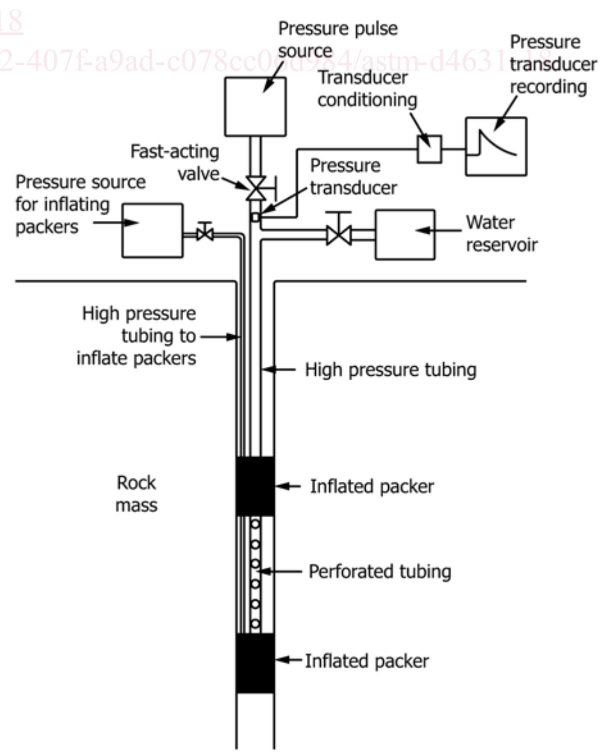

FIG. 2 Schematic of Test Equipment

7.1 *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 ($P/P_o = 0.5$).

7.2 *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 0.5 m in length or more, with an applied pressure equal to the excess maximum pulse pressure or more to be applied to the packed-off interval and less than the formation fracture pressure at that depth.

7.3 *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 when practicable of ±3 kPa (±0.4 psi), including errors introduced by the recording system, and a resolution when practicable of 1 kPa (0.15 psi).

7.4 *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 (**5**)).

7.5 *Water*—Water used in this test shall be potable. It will be clean and compatible with the formation without dispersed solids.

8. Procedure

8.1 *Drilling Test Holes:*

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

8.1.2 *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.

8.1.3 *Test Holes Cored*—Core the test holes through zones of potential interest to provide information for locating test intervals (D2113). The selection of drilling fluids should consider the quality of the borehole that will be achieved, and the ease or difficulty of later washing and cleaning of the borehole surface without plugging with additives or cuttings. The use of polymer drilling fluids is recommended.

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

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

8.1.6 *Washing Test Holes*—The test holes must not contain material when practicable 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.

8.2 *Test Intervals:*

8.2.1 *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.

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

8.2.3 *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.

8.2.4 *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.

8.3 *Test Water:*

8.3.1 *Water 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. Potable water is generally acceptable.

8.3.2 *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.

8.4 *Testing:*

8.4.1 *Filling and Purging System*—Allow time after washing the test hole for induced formation pressures to dissipate. Once the packers have been set, slowly fill the tubing string and packed-off interval with water to make sure that air bubbles will not be trapped in the test interval and tubing.

8.4.2 *Pressure Pulse Test*—This range of pressures is in most cases sufficiently low to reduce the potential for the distortion of fractures adjacent to the test hole, but the pressure should not exceed the potential principal ground stress. Record the resulting pressure pulse and decay transient detected by the pressure transducer as a function of time to the nearest 1 kPa (0.15 psi). A typical record is shown in Fig. 3.

8.4.2.1 Before the pressure pulse test can be started it is necessary to reliably estimate the natural pressure in the test interval. See 7 and Fig. 2 for a description of a method to prepare the system for the pulse test. After the pressure is at, or