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Standard Test Method for Determining Transmissivity and Storage Coefficient of Low-Permeability Rocks by In Situ Measurements Using the Constant Head Injection Test[1]

This standard is issued under the fixed designation D 4630; 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 constant head injection.

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.

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 *Descriptions of Terms Specific to This Standard:*

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

$$T = K \cdot b$$

where:
K = hydraulic conductivity.

The hydraulic conductivity, *K*, is related to the permeability, *k*, as follows:

$$K = k\rho g/\mu$$

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

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

$$S = S_s \cdot b$$

where:
S_s = specific storage.

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

$$S_s = \rho g \,(C_b + nC_w)$$

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 G—dimensionless function.

2.2.4 K—hydraulic conductivity (LT^{-1}).

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

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

2.2.6 Q—excess water flow rate (L^3T^{-1}).

2.2.7 Q_o—maximum excess water flow rate (L^3T^{-1}).

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

2.2.9 S_s—specific storage (L^{-1}).

2.2.10 T—transmissivity (L^2T^{-1}).

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).

2.2.15 n—porosity (dimensionless).

2.2.16 r_w—radius of test hole (L).

2.2.17 t—time elapsed from start of test (T).

2.2.18 α—dimensionless parameter.

2.2.19 μ—viscosity of water ($ML^{-1}T^{-1}$).

2.2.20 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.

3.2 The test itself involves rapidly applying a constant pressure to the water in the packed-off interval and tubing string, and recording the resulting changes in water flow rate. The water flow rate is measured by one of a series of flow meters of different sensitivities located at the surface. The

[1] This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Ground Water and Vadose Zone Investigations.

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initial transient water flow rate is dependent on the transmissivity and storativity of the rock surrounding the test interval and on the volume of water contained in the packed-off interval and tubing string.

4. Significance and Use

4.1 *Test Method*—The constant pressure injection test method is used to determine the transmissivity and storativity of low-permeability formations surrounding packed-off intervals. Advantages of the method are: (*a*) it avoids the effect of well-bore storage, (*b*) it may be employed over a wide range of rock mass permeabilities, and (*c*) it is considerably shorter in duration than the conventional pump and slug tests used in more permeable rocks.

4.2 *Analysis*—The transient water flow rate data obtained using the suggested test method are evaluated by the curve-matching technique described by Jacob and Lohman **(1)**[2] and extended to analysis of single fractures by Doe *et al.* **(2)**. If the water flow rate attains steady state, it may be used to calculate the transmissivity of the test interval **(3)**.

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.

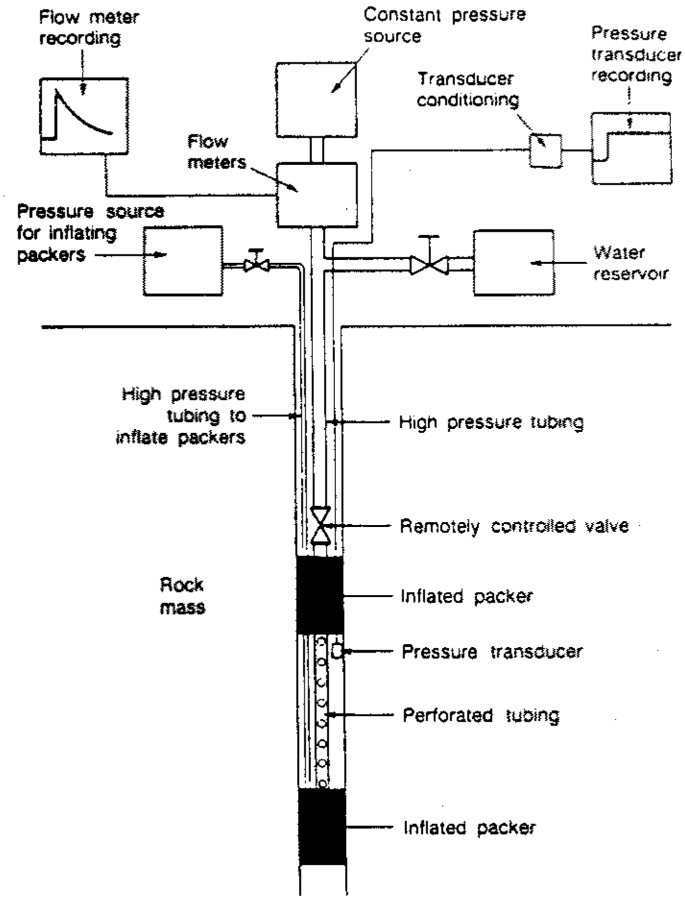

FIG. 1 Equipment Schematic

5. Apparatus

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

5.1 *Source of Constant Pressure*—A pump or pressure intensifier shall be capable of providing an additional amount of water to the water-filled tubing string and packed-off test interval to produce a constant pressure of up to 1 MPA (145 psi) in magnitude, preferably with a rise time of less than 1 % of one half of the flow rate decay (Q/Q_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 constant pressure to be applied to the packed-off interval and less than the formation fracture pressure at that depth.

5.3 *Pressure Transducers*—The pressure shall be measured as a function of time, with the transducer located in the packed-off test interval. 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 *Flow Meters*—Suitable flow meters shall be provided for measuring water flow rates in the range from 10^3 cm^3/s to 10^{-3} cm^3/s. Commercially available flow meters are capable of measuring flow rates as low as 10^2 cm^3/s with an accuracy of ±1 % and with a resolution of 10^{-5} cm^3/s; these can test permeabilities to 10^{-3} md based on a 10-m packer spacing. Positive displacement flow meters of either the tank type (Haimson and Doe **(4)** or bubble-type (Wilson *et al.* **(3)** are capable of measuring flow rates as low as 10^{-3} cm^3/s; these can test permeabilities to 10^{-4} md based on a 10-m packer spacing.

5.5 *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 constant pressure shall be attached to the steel tubing at the surface. A remotely controlled down-hole valve, located in the steel tubing immediately above the upper packer, shall be used for shutting in the test interval and for instantaneous starting of tests.

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, preferably at right angles.

6.1.2 *Test Hole Quality*—The drilling procedure shall

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

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. Whenever possible, also use sonic logs and the acoustic televiewer. 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*—Determine test intervals from the core descriptions, geophysical borehole logs, and, if necessary, from visual inspection of the borehole with a borescope or TV 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 three or more tests in each rock type, if homogeneous. If the rock is not homogeneous, the sets 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*—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. Close the downhole valve to shut in the test interval, and allow the test section pressures (as determined from downhole pressure transducer reading) to dissipate.

6.4.2 *Constant Pressure Test*—Pressurize the tubing, typically to between 300 and 600 kPa (50 to 100 psi) above the shut-in pressure. This range of pressures is in most cases sufficiently low to minimize distortion of fractures adjacent at the test hole, but in no case should the pressure exceed the minimum principal ground stress. It is necessary to provide sufficient volume of pressurized water to maintain constant pressure during testing. Open the down-hole valve, maintain the constant pressure, and record the water flow rate as a function of time. Then close the down-hole valve and repeat the test for a higher value of constant test pressure. A typical record is shown in Fig. 2.

7. Calculation and Interpretation of Test Data

7.1 The solution of the differential equation for unsteady state flow from a borehole under constant pressure located in an extensive aquifer is given by Jacob and Lohman **(1)** as:[3]

$$Q = 2\pi TP\, G(\alpha)/\rho g, \tag{1}$$

where:

Q = water flow rate,
T = transmissivity of the test interval,
P = excess test hole pressure,
ρ = water density,
g = acceleration due to gravity, and
$G(\alpha)$ = function of the dimensionless parameter α:

$$\alpha = Tt/Sr_w^2 \tag{2}$$

where:

t = time elapsed from start of test,
S = storativity, and
r_w = radius of the borehole over the test interval.

7.1.1 In Fig. 2, the flow rate in the shut-in, packed-off interval is considered constant. In those cases where the response of the shut-in interval is time dependent, interpretation of the constant pressure test is unaffected, provided the time dependency is linear.

7.2 To determine the transmissivity, T, and storativity, S, data on the water flow rate at constant pressure as a function of time are plotted in the following manner **(1)**.

7.2.1 First, plot a type curve log of of the function $G(\alpha)$ versus α where values of $G(\alpha)$ are given in Table 1.

7.2.2 Second, on transparent logarithmic paper to the same scale, plot values of the log of flow rate, Q, versus values of the log of time, t at the same scale as the type curve.

7.2.3 Then, by placing the experimental data over the theoretical curve, the best fit of the data to the curve can be made.

7.2.4 Determine the values of transmissivity, T, and storativity, S, using Eqs. 1 and 2 from the coordinates of any point in both coordinate systems.

8. Report

8.1 The report shall include the following:

8.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the constant pressure test program, and the characteristics of rock mass tested.

8.1.1.1 *Scope of Testing Program:*

8.1.1.1.1 Report the location and orientation of the boreholes and test intervals. For tests in many boreholes or in a variety of rock types, present the matrix in tabular form.

8.1.1.1.2 Rationale for test location selection, including

[3] For bounded aquifers the reader is referred to Hantush **(5)**.

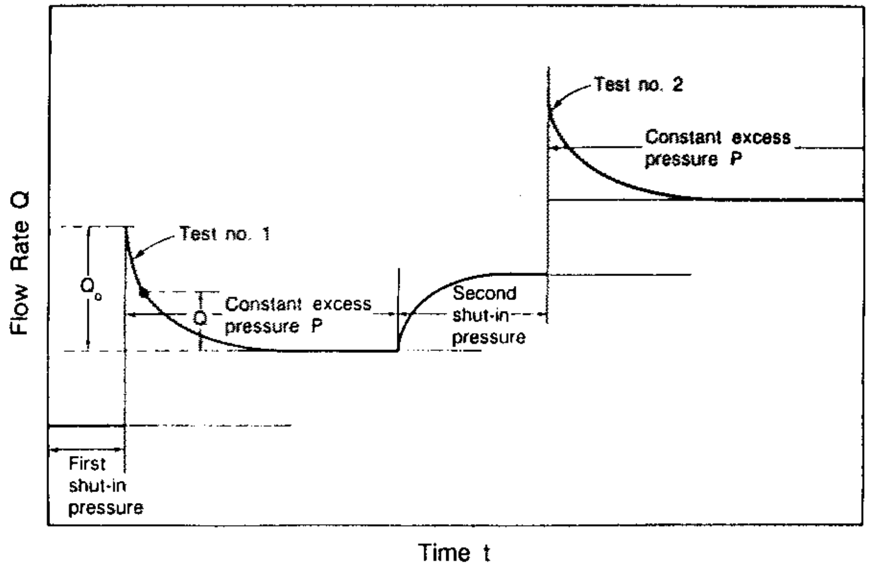

FIG. 2 Typical Flow Rate Record

the reasons for the number, location, and size of test intervals.

8.1.1.1.3 Discuss in general terms limitations of the testing program, stating the areas of interest which are not covered by the testing program and the limitations of the data within the areas of application.

8.1.1.2 *Brief Description of the Test Intervals*—Describe rock type, structure, fabric, grain or crystal size, discontinuities, voids, and weathering of the rock mass in the test intervals. A more detailed description may be needed for certain applications. In a heterogeneous rock mass or for several rock types, many intervals may be described; a tabular presentation is then recommended for clarity.

8.1.2 *Test Method:*

8.1.2.1 *Equipment and Apparatus*—Include a list of the equipment used for the test, the manufacturer's name, model number, and basic specifications for each major item, and the date of last calibration, if applicable.

8.1.2.2 *Procedure*—State the steps actually followed in the procedure for the test.

8.1.2.3 *Variations*—If the actual equipment or procedure deviates from this test method, note each variation and the reasons. Discuss the effects of any deviations upon the test results.

8.1.3 *Theoretical Background:*

8.1.3.1 *Data Reduction Equations*—Clearly present and fully define all equations and type curves used to reduce the data. Note any assumptions inherent in the equations and type curves and any limitations in their applications and discuss their effects on the results.

8.1.3.2 *Site Specific Influences*—Discuss the degree to which the assumptions contained in the data reduction equations pertain to the actual test location and fully explain any factors or methods applied to the data to correct for

TABLE 1 Values of $G(\alpha)$ for Values of α Between 10^{-4} and 10^{12} [A]

	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	10	10^2	10^3
1	56.9	18.34	6.13	2.249	0.985	0.534	0.346	0.251
2	40.4	13.11	4.47	1.716	0.803	0.461	0.311	0.232
3	33.1	10.79	3.74	1.477	0.719	0.427	0.294	0.222
4	28.7	9.41	3.30	1.333	0.667	0.405	0.283	0.215
5	25.7	8.47	3.00	1.234	0.630	0.389	0.274	0.210
6	23.5	7.77	2.78	1.160	0.602	0.377	0.268	0.206
7	21.8	7.23	2.60	1.103	0.580	0.367	0.263	0.203
8	20.4	6.79	2.46	1.057	0.562	0.359	0.258	0.200
9	19.3	6.43	2.35	1.018	0.547	0.352	0.254	0.198
10	18.3	6.13	2.25	0.985	0.534	0.346	0.251	0.196
	10^4	10^5	10^6	10^7	10^8	10^9	10^{10}	10^{11}
1	0.1964	0.1608	0.1360	0.1177	0.1037	0.0927	0.0838	0.0764
2	0.1841	0.1524	0.1299	0.1131	0.1002	0.0899	0.0814	0.0744
3	0.1777	0.1479	0.1266	0.1106	0.0982	0.0883	0.0801	0.0733
4	0.1733	0.1449	0.1244	0.1089	0.0968	0.0872	0.0792	0.0726
5	0.1701	0.1426	0.1227	0.1076	0.0958	0.0864	0.0785	0.0720
6	0.1675	0.1408	0.1213	0.1066	0.0950	0.0857	0.0779	0.0716
7	0.1654	0.1393	0.1202	0.1057	0.0943	0.0851	0.0774	0.0712
8	0.1636	0.1380	0.1192	0.1049	0.0937	0.0846	0.0770	0.0709
9	0.1621	0.1369	0.1184	0.1043	0.0932	0.0842	0.0767	0.0706
10	0.1608	0.1360	0.1177	0.1037	0.0927	0.0838	0.0764	0.0704

[A] From Jacob and Lohman (1).

Data Sheet

Project ______	Test No. ______
Test Location ______	Borehole No. ______
Rock Type ______	Borehole Dip and Dip Direction ______
Date ______	Measured Depth of Test to Top Packer, m ______
Testing by ______	Borehole Diameter, mm ______
	Rock Temperature, °C ______

Equipment Description	Serial No.	Date of last Calibration

Length of Packed-off Interval, m ______	Packer Pressure, kPa ______
Length of Tubing Above Top Packer, m ______	Tubing ID, mm ______
Water Temperature, °C ______	Shut-in Borehole Pressure, kPa ______
	Constant Water Pressure, kPa ______

FIG. 3 Data Sheet for In Situ Measurement of Transmissivity and Storativity Using the Constant Head Injection Test

departures from the assumptions of the data reduction equations.

8.1.4 *Results:*

8.1.4.1 *Summary Table*—Present a table of results, including the types of rock and discontinuities, the average values of the transmissivity and storativity, and their ranges and uncertainties.

8.1.4.2 *Individual Results*—Present a table of results for individual tests, including test number, interval length, rock types, value of constant pressure transmissivity and storativity, and flow rate as a function of time.

8.1.4.3 *Graphic Data*—Present water flow rate versus time curves for each test, together with the appropriate type curves used for their interpretation.

8.1.4.4 *Other*—Other analyses or presentations may be included as appropriate, for example: (*a*) discussion of the characteristic of the permeable zones, (*b*) histograms of results, and (*c*) comparison of results to other studies or previous work.

8.1.5 *Appended Data*—Include in an appendix a completed data form (Fig. 3) for each test.

9. Precision and Bias

9.1 *Error Estimate:*

9.1.1 Analyze the results using standard statistical methods. Calculate all uncertainties using a 95 % confidence interval.

9.1.2 *Measurement Error*—Evaluate the errors in transmissivity and storativity associated with a single test. This includes the combined effects of flow rate determination, measurement of time, and type curve matching.

9.1.3 *Sample Variability*—For each rock or discontinuity type, calculate, as a minimum, the mean transmissivity and storativity and their ranges, standard deviations, and 95 % confidence limits for the means. Compare the uncertainty associated with the transmissivity and storativity for each rock type with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

10. Keywords

10.1 borehole; constant head testing; flow; in situ; faultzones; field testing; flow and flow rate; permeability; pressure testing; rock; saturation; storativity; transmissivity; viscosity; water; water saturation

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