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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 D 4631; 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.

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 = 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:

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

where:

ρ = fluid density,

μ = 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:

$$S = S_s \cdot b$$

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:

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

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 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 $[L^2]$.

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

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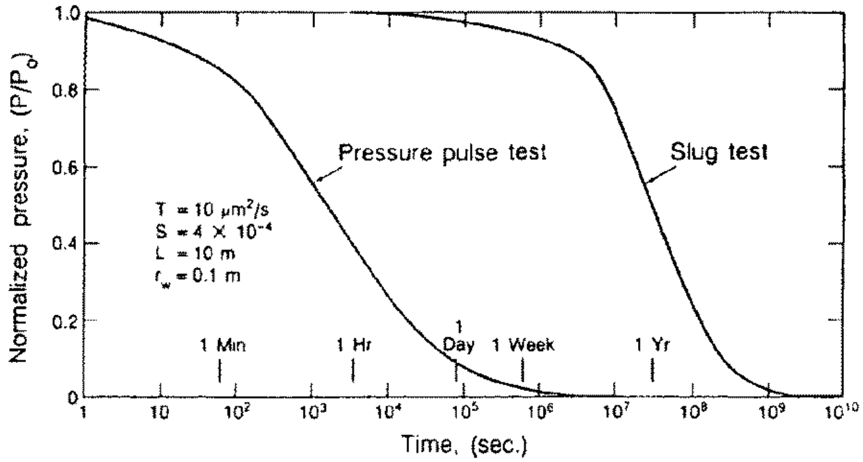

FIG. 1 Comparative Times for Pressure Pulse and Slug Tests

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—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 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

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

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

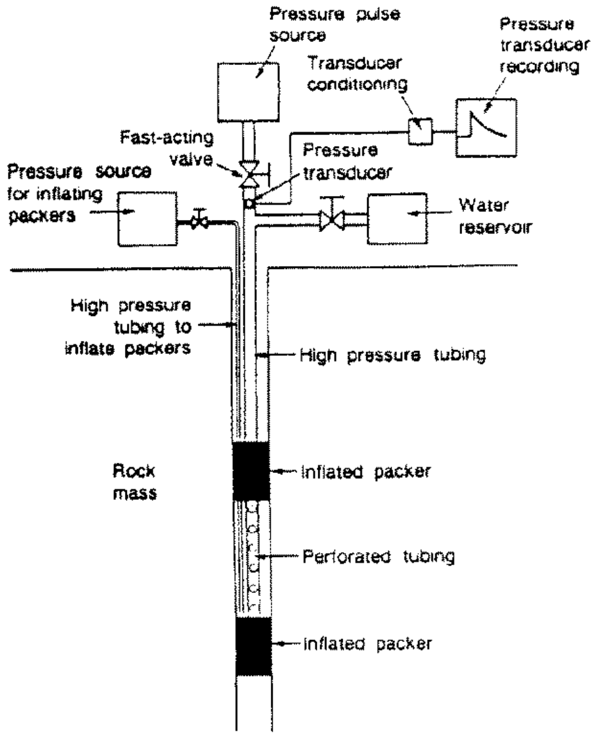

FIG. 2 Schematic of Test Equipment

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.

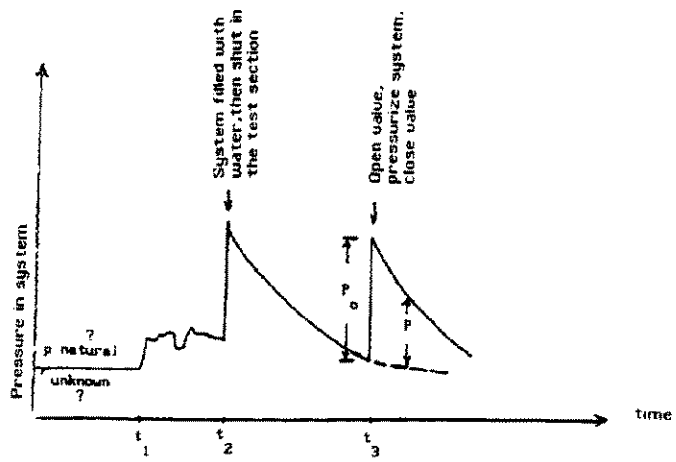

FIG. 3 Typical Pressure Record

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 Figs. 1 and 3. The pulse decay is given as follows:

$$\frac{P}{P_o} = F(\alpha,\beta) \tag{1}$$

where:
α and β = dimensionless parameters given by:
to:

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

and:

$$\beta = \pi T t / V_w C_w \rho g \tag{3}$$

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,
ρ = 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

$$C_{obs} = \frac{dv/v}{dp} \tag{4}$$

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, α, is larger or smaller than 0.1. Since the value of α is not known *a priori*, the test data are first analyzed by the method applicable to $\alpha < 0.1$. If this analysis indicates that $\alpha > 0.1$, then that method is used.

7.2.1 For $\alpha < 0.1$, the data are analyzed by the method described by Cooper et al **(4)**, in which the family of curves shown in Fig. 4 for $F(\alpha, \beta)$ as a function of β for various values of α are used. Observed values of P/P_o are plotted as a function of time, t, on semilogarithmic paper of the same scale, and are matched with a type curve by keeping the β and t axes coincident and moving the plots horizontally.

7.2.2 The expressions corresponding to α and β in Eqs 1 and 2, the α value of the matched type curve, and the β and t values from a match point are used to determine the transmissivity, T, and the storage coefficient, S, of the tested interval. Bredehoeft and Papadopulos **(1)** indicate that this procedure yields good estimates of the transmissivity when ≤ 0.1, but that the storage coefficient could be of questionable reliability for values of $\alpha < 10^{-5}$.

7.2.3 For $\alpha > 0.1$, Bredehoeft and Papadopulos **(1)** recommend the use of the family of curves shown in Fig. 5 for $F(\alpha, \beta)$ as a function of the product $\alpha\beta = \left(\frac{\pi^2 r_w{}^2 TSt}{(V_w C_w{}^\rho g)^2}\right)$ to interpret the data. Matching of the observed values of P/P_o plotted as a function of t with a type curve is performed in the same manner as indicated previously for $\alpha \leq 0.1$. In this way, the product TS and S are determined. Analysis with the type curves shown in Fig. 5 provides an indication as to whether the data are adequate for identifying both α and β and, hence, determining both S and T, or whether the data fall in the range where only the product TS can be determined.

7.3 Wang et al **(2)** present an alternative method of analyzing pressure pulse data involving analytical solutions for pulse decay in single fractures of both infinite and finite

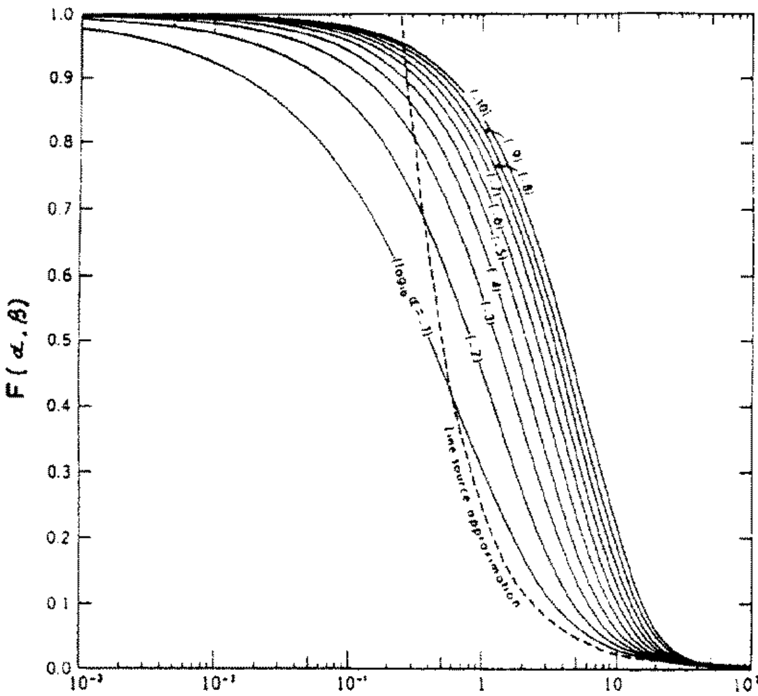

FIG. 4 Type Curves of the Function $F(\alpha, \beta)$ Against the Parameter β for Different Values of α

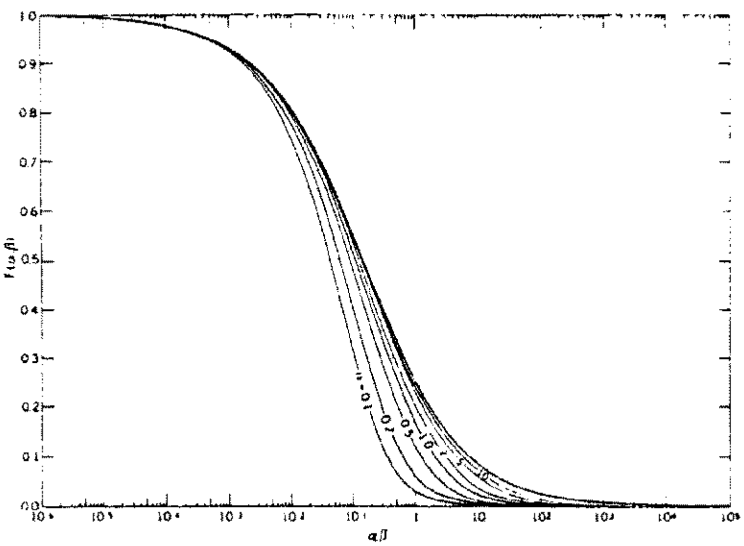

FIG. 5 Type Curves of the Function $F(\alpha, \beta)$ Against the Product Parameter $\alpha\beta$

extent. Recognizing that finite fracture geometry introduces errors in the interpretation of the pulse decay data, Wang suggests a method that uses data from elapsed times before the fracture boundaries begin to influence the pressure data. Wang found by linear regression of calculated decay pressure versus time an empirical expression for the fracture aperture of the following form:

$$\begin{aligned}\log (e/10^6) = & -0.32 \log (t) + C \\ & + 0.32 [2 \log (r_w/0.04) \\ & + \log (2.394\mu C_w \times 10^{12})] \\ & + 0.333 \log (L/2).\end{aligned} \quad (5)$$

where:

e = parallel-plate equivalent aperture, m,
t = time, s,
r_w = borehole radius, m,
μ = water viscosity, mPa·s,
C_w = water compressibility, 1/Pa,
L = length of the packed-off interval, m, and
C = constant that depends on the fraction of pulse decay, as follows:

Fraction of pulse decay, $(P_o - P)/P_o$	0.05	0.10	0.15
Wang constant, C:	1.09	1.20	1.27

7.3.1 Wang shows that in test zones containing two fractures of different apertures, the wider fracture dominates the early time behavior. The early pressure pulse decay therefore reflects the major fracture only. Doe et al (**6**) view individual fractures as confined aquifers whose transmissivities are given by the cubic relationship:

$$T = \rho g e^3 / 12\mu \quad (6)$$

Thus, Eq 6 provides transmissivity in terms of a parallel-plate equivalent fracture aperture calculated from Eq 5.

7.3.2 Equations 5 and 6 can be solved for the early-time pressure pulse decay data to provide a transmissivity value for the test interval from the calculated parallel-plate equivalent aperture.

8. Report

8.1 Report the following information:

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

8.1.2 *Scope of Testing Program:*

8.1.2.1 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 test matrix in tabular form.

8.1.2.2 Rationale for test location selection, including the reasons for the number, location, and size of test intervals.

8.1.2.3 Discuss in general terms the 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.

8.1.3 *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.

8.1.4 *Test Method:*

8.1.4.1 *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.

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

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

8.1.5 *Theoretical Background:*

8.1.5.1 *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.

8.1.5.2 *Site Specific Influences*—Discuss the degree to which the assumptions contained in the data reduction

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 ______________________ Maximum Pulse Pressure, kPa ______________________

Pulse Decay Time, s ______________________

FIG. 6 Data Sheet for In Situ Measurement of Transmissivity and Storativity Using the Pressure Pulse Technique

equations pertain to the actual test location and fully explain any factors or methods applied to the data to correct for departures from the assumptions of the data reduction equations.

8.1.6 *Results:*

8.1.6.1 *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.

8.1.6.2 *Individual Results*—Present a table of results for individual tests, including test number, interval length, rock types, transmissivity and storativity, and pressure pulse amplitude and decay time (or recording time, if the decay is incomplete).

8.1.6.3 *Graphic Data*—Present pressure pulse decay versus time curves for each test, together with the appropriate type curves used for their interpretation.

8.1.6.4 *Other*—Other analysis or presentations may be included as appropriate, for example: (*1*) discussion of the characteristics of the permeable zones, (*2*) histograms of results, and (*3*) comparison of results to other studies or previous work.

8.1.7 *Appended Data*—Include in an appendix a completed data form (Fig. 6) for each test.

9. Precision and Bias

9.1 It is not practicable to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true reference values exist.

10. Keywords

10.1 borehole drilling; discontinuities; fault zones; field testing flow and flow rate; ground water; permeability; pressure testing; pulse testing; rock; saturation; storativity; transmissivity; viscosity; water; water saturation

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