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VOLUME I: FIELD OPERATIONS (FO)
VOLUME II: GROUNDWATER (GW)
VOLUME III: GEOTECHNICAL (GT)
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ADMIN RECORD

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EG&G ROCKY FLATS PLANT	**Manual:**	**5-21000-OPS**
EMD MANUAL OPERATION SOP	**Procedure No.:**	**GW.3, Rev.2**
	Page:	**1 of 14**
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Category 2	**Organization:**	**Environmental Management**

TITLE:
PUMP-IN BOREHOLE PACKER TESTING

Approved By:
(Name of Approver) (Date)

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2.0 PURPOSE AND SCOPE

This standard operating procedure (SOP) describes procedures that will be used at the Rocky Flats Plant (RFP) to conduct in situ pump-in borehole hydraulic conductivity tests in uncased portions of boreholes in bedrock, using packers. Various packer testing arrangements can be used for in situ hydraulic conductivity tests in uncased portions of boreholes.

Relatively large-scale, multiple-well pump-out tests are generally preferred over single-well tests such as slug tests and packer tests for evaluating aquifer characteristics. However, the information obtained using less-costly, single-hole packer tests is frequently useful and cost-effective, particularly in relatively low-permeability formations. A standard operating procedure addendum (SOPA) will describe project-specific testing requirements.

This SOP describes packer testing equipment and procedures and Quality Assurance/Quality Control (QA/QC) that will be used for field data collection and documentation in order to attain acceptable standards of accuracy, precision, comparability, representativeness, and completeness.

3.0 PERSONNEL QUALIFICATIONS

Personnel conducting pump-in borehole packer tests will be geologists, geotechnical engineers, or field technicians with an appropriate amount of applicable field experience or on-the-job training under the supervision of another qualified person. All personnel performing this procedure are required to have 40-hour OSHA classroom training which meets the Department of Labor requirements 29 CFR 1910.120 (e)(3)(i).

4.0 REFERENCES

4.1 SOURCE REFERENCES

The following is a list of refernces reviewed prior to the writing of this procedure:

A Compendium of Superfund Field Operations Methods. EPA/540/P-87/001. December 1987.

ASTM D 4630-86. Standard Test Method for Determining Transmissivity and Storativity of Low-Permeabiliiy Rocks by In-Situ Measurements Using the Constant Head Injection Test. December 1986.

ASTM D 4631-86. Standard Test Method for Determining Transmissivity and Storativity of Low-Permeabiliiy Rocks by In-Situ Measurements Using the Pressure Pulse Technique. December 1986.

Groundwater Monitoring. U.S. DOE, Water and Power Resources Service, 1981.

Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA. Interim Final. October 1988

RCRA Groundwater Monitoring Technical Enforcement Guidance Document. EPA. OSWER9950. Washington D.C. September 1986.

RCRA Facility Investigation Guidance. Interim Final. May 1989.

4.2 INTERNAL REFERENCES

Related SOPs cross-referenced by this SOP are as follows:

- SOP GT.2, Drilling and Sampling Using Hollow-Stem Auger Techniques
- SOP GT.4, Rotary Drilling and Rock Coring
- SOP GW.1 Water Level Measurements in Wells and Piezometers

5.0 EQUIPMENT AND PROCEDURES

A packer test is an in situ test used to measure the apparent hydraulic conductivity of the soil or rock surrounding a borehole by measuring the flow rate of water pumped into or out of a discrete depth interval of the borehole that is isolated by rubberized inflatable packers under known pressures. This SOP addresses "pump-in" tests, in which water is injected into the test interval at constant applied pressure (constant head), or a constant rate of flow, or as a pressure pulse. Packer tests will be conducted in portions of boreholes drilled in bedrock indicated by the Field Sampling Plan (FSP). Water injected into boreholes during packer testing will be RFP potable water or commercially available distilled water. RFP tap water will be used unless the FSP or a SOPA states otherwise. The Quality Assurance Addendum (QAA) will address tap water testing requirements. Single packers, double packers, or straddle packers will be used to isolate a desired length of borehole for testing. Downhole packer test equipment will be decontaminated between boreholes according to SOP FO.3, General Equipment Decontamination.

5.1 EQUIPMENT

Packer tests will be conducted using an arrangement that will satisfy the requirements of the FSP. A straddle packer arrangement can be used to test a segment of a borehole isolated between two packers, or a single packer can be used to test a segment of borehole between the hole bottom and the packer. In some cases, for instance when testing very low-permeability formations, a single packer test tool may be modified into a double packer test tool arrangement that has a pressure sensor between the two packers to help detect slow leaks around the packers. This type of double packer test tool arrangement may be further expanded and modified into a straddle packer test tool that has two packers positioned above and two packers below the test interval.

The packers will be of a diameter compatible with the borehole diameter (see manufacturer's recommendations) so the test zone can be properly isolated (i.e., sealed off from other depth intervals in the boring). Electronic pressure transducers with an accuracy of 0.1 pounds per square inch (psi) or better will be placed above, below, and within the test zone to monitor test pressures and to check for proper sealing of the packers. The transducers will be attached to electronic data logging equipment capable of monitoring and recording pressure versus time. Example schematic diagrams of packer tests set-ups are included in Appendixes A and B.

Because of fluctuations in pressure that can occur using conventional pumping equipment, the surface equipment used for water injection will consist of a water supply reservoir pressurized with compressed gas (nitrogen or air). The supply reservoir will be attached to the test section with rigid water-tight steel tubing. For relatively high injection rates (greater than approximately 0.5 gallon per minute [gpm]), the change in water level in the reservoir will be used to calculate flow quantity by means of a graduated transparent tube in parallel with the reservoir tank. For low injection rates, a variable-area flow meter system capable of measuring flow rates as low as 0.001 gpm will be used. To cover the range in flow rates between 0.5 and 0.001 gpm, the flow meter system will consist of at least three individual flow meters in a common manifold system with appropriate by-pass and shut-off valves, so flow may be switched from one meter to another during a test, if necessary. The diameters of the pressure tank and flow meters will provide for overlap in the measurement ranges of the equipment. The reservoir and flow tanks will be connected by water-tight steel tubing through the upper packer(s) to allow injection of water into the test interval. A fast-acting, remotely controlled shut-in valve will be placed approximately 2 feet above the upper packer.

If flow rates are high (i.e., if the reservoir empties in less than the 20-minute minimum test duration), an alternative injection system will be required. In this situation, a conventional packer test setup using clean water pumping equipment and a manifold system with an impeller-type flow meter and appropriate flow restriction and by-pass valves will be used. However, there is a potential for large volumes of water injected to alter groundwater chemistry in nearby wells or to influence contaminant plumes. In any case, no more than 50 gallons of water will be injected slowing during a packer test without the approval of the EG&G project manager.

5.2 PROCEDURES

Packer tests will be conducted in general accordance with Subsections 6.3 and 6.4 of ASTM D 4630, 'Standard Test Method for Determining Transmissivity and Storativity of Low-Permeability Rocks by In-Situ Measurements Using the Constant Head Injection Test,' and Subsections 6.3 and 6.4 of ASTM D 4631, 'Standard Test Method for Determining Transmissivity and Storativity of Low - Permeability Rocks by In-Situ Measurements Using the Pressure Pulse Technique.' These references are presented in Appendixes A and B, respectively. With the exception of the injection pressures, the procedures will be consistent with the referenced sections. Other portions of the referenced methods should be read because they are also applicable and contain useful information, but are not necessarily a requirement of this SOP.

A borehole will be drilled and, if required, prepared so it is suitable for testing. The project data quality objectives and subsurface conditions will dictate appropriate preparation. The objectives of borehole preparation are to provide a borehole that can be sealed with packers, to provide a borehole sidewall with hydraulic properties similar to those of the formation, and to leave water in the borehole similar in physical characteristics to the formation water. Depending on the formation characteristics and drilling methods, borehole preparation activities may consist of flushing and/or purging. Geophysical and caliper borehole logs may be used to select borehole zones for testing and to evaluate whether difficulties seating packers are likely to be encountered. If the borehole is flushed and/or purged, 24 hours will be allowed before testing to allow induced pressures (pressure transients) in the formation to dissipate.

After a suitable borehole has been provided, testing will commence at the intervals predetermined or determined based on information from the geophysical and/or caliper logs. The packers will be inserted at the desired level in the borehole and inflated to seal off the test section. If the borehole is not already filled with water to a level above the upper packer, it will be before the packers are inflated. A packer inflation pressure approximately 200 psi above the maximum anticipated test pressure should be used. However, if there are problems with rupturing packers due to yielding of the rock at this pressure, lower inflation pressures may be used. The probability of leakage will be increased at lower packer inflation pressures.

Once the test is set up as described above, various procedures may be used, depending on project requirements. The three basic types of tests are:

1. Constant head

2. Constant rate of flow

3. Pressure pulse

In general, the constant head and pressure pulse tests are preferred for relatively low-permeability formations while the constant rate of flow test is frequently used in formations with relatively high-permeability.

5.2.1 Constant Head Test

After the packers have been set and the test section and supply tube filled with water in a manner such that there is no entrapped air, the downhole valve will be shut and the shut-in test section pressures allowed to dissipate (as determined from the pressure transducer in the test section).

After the shut-in pressure has dissipated and the stable pressure recorded in PSI, the reservoir pressure will be increased to the desired test pressure and the downhole valve opened. Readings of flow rate versus time will be obtained while the pressure (head) is maintained at approximately a constant value. A record of pressure versus time for each of the three pressure transducers will also be kept. Injection of water into the test section will continue at a constant head until the flow rate stabilizes, or a minimum of 20 minutes. Conditions will be considered stable when at least 3 consecutive five-minute flow readings do not vary by more than 10 percent. Test durations will frequently be 30 to 60 minutes. However, durations of as long as 4 to 6 hours may sometimes be required for conditions to stabilize. If test durations longer than 60 minutes occur regularly on a project, the EG&G project manager should evaluate the cost-effectiveness of the testing program and modify it if warranted. If either of the pressure transducers above and below the test section show a rapid pressure response to a pressure increase in the test section, the packers will be reseated to eliminate leakage around them. The test interval depth will have to be modified if the packers cannot be properly seated at the original target depth. The EG&G project manager will be involved in determining any offset test intervals unless the offset is small.

The project-specific test program may require several increasing pressure increments for 'Stepped" tests. After each increment, the downhole valve will be shut in and the test section shut-in pressure allowed to dissipate. The maximum injection pressure at the test section must not exceed the effective overburden pressure at the test section to avoid hydraulic fracturing. Hydraulic fracturing will normally be avoided if the total hydraulic pressure in the test section does not exceed 0.5 psi per foot depth to the center of the test section. Since the head of the column of water in the tubing is approximately 0.43 psi per foot ([62.4 $lb/ft^2/ft$ depth]/[144 in^2/ft^2] = 0.43$lb/in^2/ft$ depth), this means the sum of the reservoir head above the ground surface and the pneumatic pressure applied to the reservoir should not exceed 0.07 psi per foot of depth to the test section. In other words, 0.5 psi/ft depth (total allowable) minus 0.43 psi/ft depth (head in tubing) = 0.07 psi/ft (maximum applied pressure above ground surface).

5.2.2 Constant Rate of Flow Test

The procedures for a constant rate of flow test are essentially the same as for a constant head test except that the injection rate is held constant and readings of pressure versus time are obtained. Injection of water into the test section will continue at a constant rate until the pressure stabilizes, or for a minimum of 20 minutes. Conditions will be considered stabilized when at least 3 consecutive five-minute pressure readings do not vary by more than 10 percent. Test durations will frequently be 30 to 60 minutes. However, durations of as long as 4 to 6 hours may sometimes be required for conditions to stabilize. If test durations longer than 60 minutes occur regularly on a project, the EG&G project manager should evaluate the cost-effectiveness of the testing program and modify it if warranted. The automatic data acquisition equipment will record pressure versus time. As for the constant head test, the project-specific test program may require stepped tests provided that the maximum test pressure does not exceed the maximum described in Subsection 5.2.1 to avoid hydraulic fracturing.

If relatively high flow rates (that is, if the reservoir empties in less than the 20-minute minimum test duration) are encountered, it may not be practical to use the pressurized reservoir and downhole pressure transducer test setup described herein. In this case, testing will use a more conventional packer test setup consisting of pumping equipment and a manifold system with an impeller-type flow meter and appropriate flow restriction and bypass valves. If the transducer in the test section is ineffective due to turbulence, a pressure gauge on the manifold system may be used. Testing with this equipment may also follow the constant head test procedure; however, in either case, it may be difficult to accurately control flow rates and pressures.

5.2.3 Pressure Pulse Test

Borehole preparation and packer placement will be the same as described in Subsection 5.2. The pressure pulse test can use the same test setup as described for the constant head test, provided the downhole shut-in valve can be opened and closed rapidly. Alteratively, the downhole shut-in valve may be replaced with a fast-acting valve between the pressure source and water supply tube. Similarly, the pressure transducer in the test section may be relocated to the water-supply line at the top of the borehole between the fast-acting valve and the test section (see Figure 2 in ASTM D 4631).

Once the packers are in place, the water supply tubing will be rapidly pressurized and then shut in by opening and closing the fast-acting valve. The resulting pressure pulse and decay transient will be recorded by the electronic data logging equipment starting at the time the valve is closed. The transducers above and below the test section will also be read to check for leaks around the packers. If leakage occurs, the packers will be reseated to eliminate leakage around them. The test depth interval will have to be modified if the packers cannot be properly seated at the original target depth. The EG&G project manager will be involved in determining any offset test intervals.

5.3 METHODS OF ANALYSIS

For each injection test, data analysis will be conducted using a selected analytical procedure appropriate for the hydraulic conditions and estimated flow patterns. The project hydrogeologist responsible for interpreting the test results will select the analytical methods used. The appendixes discuss some available analytical techniques. The methods used may include those presented in the following published literature:

Doe, T. and J. Remer. 1980. 'Analysis of constant-head well tests in nonporous fractured rock' Proceedings, 3rd Invitational Well-testing Symposium. University of California. Berkeley. LBL-12076 pp.87-89.

Hsieh, PA., S.P., Neuman and E.S. Simpson, 1983. 'Pressure testing of fractured rocks - a methodology employing three-dimensional cross-hole tests.' Department of Hydrology and Water Resources. University of Arizona. NUREG Publication CR-3213.

Hsieh, PA., S.P. Neuman, G.)L Stiles, and E.S. Simpson. 1985. 'Field determination of the three-dimensional hydraulic conductivity tensor of anisotropic media: 2. methodology and application to fractured rocks.' Water Resources Research. Volume 2 No. 1 pp. 16671676.

Hvorslev, MJ. 195 Time lag and soil permeability in groundwater observations. Bulletin No. 36. U.S. Army Engineer Waterways Experiment Station. Vicksburg, Mississippi.

Jacob, C.E., and S.W. Lohman. 1952. 'Nonsteady flow to a well of constant drawdown in an extensive aquifer.' American Geophysical Union Transactions. V. 33. pp. 559-569.

O'Rourke, J.E., Essex, RJ. and Ranson, B.K 1977. 'Field Permeability Test Methods with Applications to Solution Mining.' prepared by Woodward-Clyde Consultants for the Bureau of Mines, U.S. Department of Interior. published by the National Technical Information Service. PB-272452. 180 pp.

Zeigler, T.W. 1976. Determination of rock mass permeability. Technical Report S-76-2. U.S. Army Engineer Waterways Experiment Station. Vicksburg, Mississippi.

6.0 DOCUMENTATION

Documentation for this SOP will include a schematic diagram of the test setup. This diagram will show the relative positions of all gauges, valves, transducers, and packer elements within the test tool string. The diagram will accompany the data records for each test. For each type of test, a data form will be developed to record flow/time/pressure data. Form GW.3A is a pump-in borehole packer test summary sheet that will be used to document borehole information and test type. It includes a checklist for required data.

The following information will be documented:

- Project identification
- Date
- Borehole identification/Elevation
- Drilling and/or Parker Testing Subcontractor
- Responsible geologist's/engineer's name
- Type of test
- Formation/rock type tested
- Top and bottom depths of Test Interval (below ground level)
- Description/Elevation of Depth Reference

- Water level in borehole before testing
- Packer inflation pressure
- Shut-in pressure/Stabilized pressure
- Data logger file name for pressure versus time data

The documentation checklist addresses the following:

- Diagram of test tool setup
- Calibration documentation
- Records of pressure and flow rates with time for constant-head and constant rate-of-flow tests (attach to test summary form)
- Pulse pressure and pulse decay time records for pressure pulse tests (attach to test summary)

US. DEPARTMENT OF ENERGY ROCKY FLATS PLANT FORM GW.3A

PUMP-IN BOREHOLE PACKER TEST SUMMARY SHEET

Project No. ________________ Date ________________________________

Borehole Identification ________________________________

Drilling and/or Packer Testing Subcontractor ________________________________

Geologist/Engineer ________________________________

Type of Test ________________________________

Formation/Rock Type Tested ________________________________

Top and Bottom Depths of Test Interval (below ground level) ________________

Description/Elevation of Depth Reference ________________________________

Water Level in Borehole Before Testing ________________________________

Packer Inflation Pressure ________________________________

Shut-in Pressure/Stabilized Pressure ________________________________

Data Logger File Name ________________________________

DOCUMENTATION CHECKLIST

Diagram of test tool setup prepared? (Y/N) by (Contractor's Representative) ____________

Documentation of calibrations received? (Y/N) by (Contractor's Representative) ____________

Documentation of flow meter calibration checks received? (Y/N) by (Contractor's Representative) ________

Documentation of gauge/transducer calibration checks received? (Y/N) by (Contractor's Representative)

____

Pressure versus time data for each gauge/transducer obtained/recorded? (Y/N) by (Contractor's Representative)

____

Flow rate versus time data obtained/recorded? (Y/N) by (Contractor's Representative) ____________

COMMENTS: ________________________________

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APPENDIX GW.3A

STANDARD TEST METHOD FOR DETERMINING TRANSMISSIVITY AND STORATIVITY OF LOW PERMEABILITY ROCKS BY IN-SITU MEASUREMENTS USING THE CONSTANT HEAD INJECTION TEST

Designation: D 4630 – 86

Standard Test Method for Determining Transmissivity and Storativity 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 may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems 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 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 *storativity, S*—the storativity (or storage coefficient) of a formation of thickness, b, is defined as follows:

$$S = S_s b$$

where:
S_s = equivalent bulk rock specific storage (ebrss).

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}).
2.2.5 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 initial transient water flow rate is dependent on the transmis-

[1] This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.12 on Rock Mechanics.

Current edition approved Oct. 31, 1986. Published December 1986.

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

sivity 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.

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

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

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 downhole 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. Procedures

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 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

TABLE 2 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).

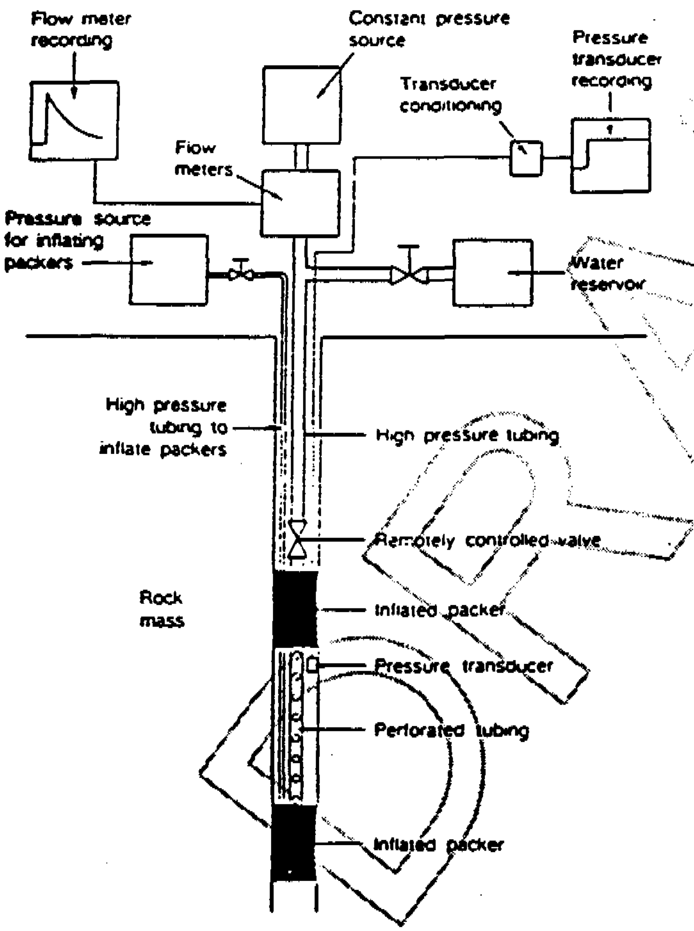

FIG. 1 Equipment Schematic

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

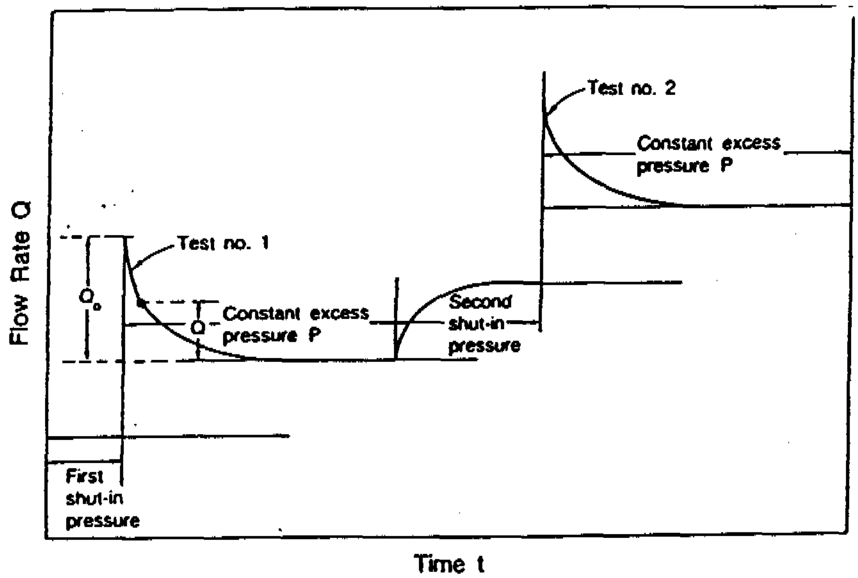

FIG. 2 Typical Flow Rate Record

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

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. Calculations 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]

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

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:

$$\alpha = Tt/Sr_w^2 \quad (2)$$

where:
t = time elapsed from start of test,

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

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 on logarithmic paper of the function $G(\alpha)$ versus α where values of $G(\alpha)$ are given in Table 2.

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

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 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 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.

REFERENCES

(1) Jacob, C. E., and Lohman, S. W., "Non-Steady Flow to a Well of Constant Drawdown in an Extensive Aquifer," Trans. American Geophys. Union, Vol 33, 1952, pp. 559–569.

(2) Doe, T. W., Long, J. C. S., Endo, H. K., and Wilson, C. R., "Approaches to Evaluating the Permeability and Porosity of Fractured Rock Masses," *Proceedings of the 23rd U.S. Symposium on Rock Mechanics*, Berkeley, 1982, pp. 30–38.

(3) Wilson, C. R., Doe, T. W., Long, J. C. S., and Witherspoon, P. A., "Permeability Characterization of Nearly Impermeable Rock Masses for Nuclear Waste Repository Siting," *Proceedings*, Workshop on Low Flow, Low Permeability Measurements in Largely Impermeable Rocks, OECD, Paris, 1979, pp. 13–30.

(4) Haimson, B. C., and Doe, T. W., "State of Stress, Permeability, and Fractures in the Precambrian Granite of Northern Illinois," *Journal of Geophysics Research*, Vol 88, 1983, pp. 7355–7371.

(5) Hantush, M. S., "Non-Steady Flow to Flowing Wells in Leaky

Aquifers," *Journal of Geophysical Research*, Vol 64, 1959, pp. 1043–1052.

(6) Zeigler, T., "Determination of Rock Mass Permeability," Tech. Rep. S-76-2, U.S. Army Eng. Waterways Exp. Stn., Vicksburg, MI, 1976, 85 pp.

Earlougher, R. C., "Advances in Well Test Analysis," *Society of Petroleum Engineers of A.I.M.E.*, New York, NY 1977.

(8) Freeze, R. A., and Cherry, J. A., *Groundwater*, Prentice-Hall, Englewood Cliffs, NJ, 1979.

(9) Shuri, F. S., Feves, M. L., Peterson, G. L., Foster, K. M., and Kienle, C. F., Public Draft: "Field and *In Situ* Rock Mechanics Testing Manual," Office of Nuclear Waster Isolation, Document ONWI-310, Section F: "*In Situ* Fluid Properties," GT-F.1 *In Situ* Permeability Measurement of Rock Using Borehole Packers, 1981.

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APPENDIX GW.3B

STANDARD TEST METHOD FOR DETERMINING TRANSMISSIVITY AND STORATIVITY OF LOW PERMEABILITY ROCKS BY IN-SITU MEASUREMENTS USING THE PRESSURE PULSE TECHNIQUE

ASTM Designation: D 4631 – 86

Standard Test Method for Determining Transmissivity and Storativity of Low Permeability Rocks by In-Situ Measurements Using the 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 may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems 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}).

2.2.4 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 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

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[1] This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.12 on Rock Mechanics.

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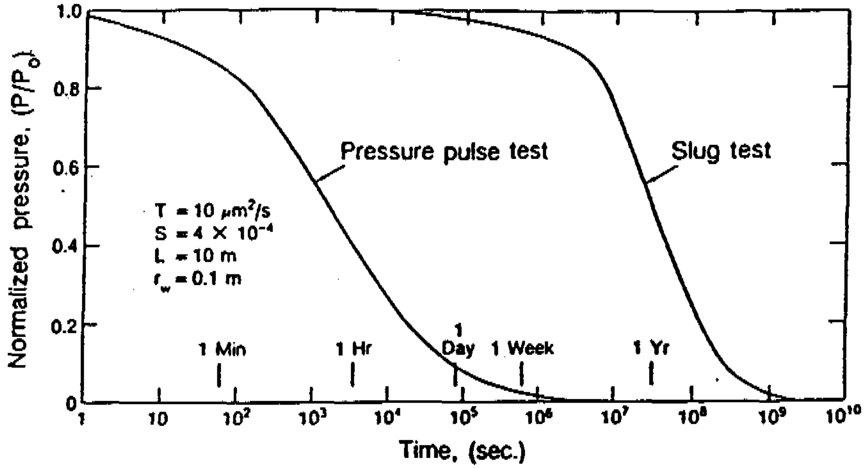

FIG. 1 Comparative Times for Pressure Pulse and Slug Tests

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. The 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.

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

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 at the surface 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

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

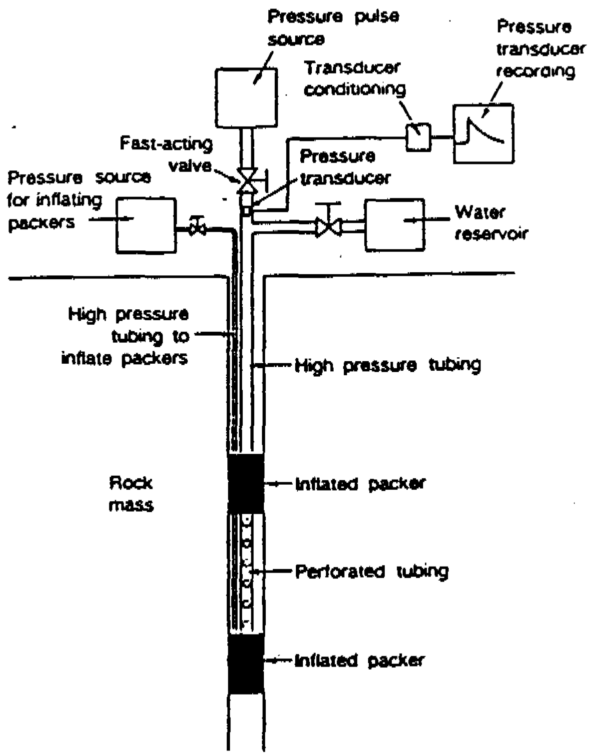

FIG. 2 Schematic of Test Equipment

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 mounted in the tubing at the surface near the pressure pump.

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 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 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*—Rapidly pressurize the tubing, typically to between 300 and 600 kPa (50 to 100 psi), and then shut in. 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.

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. 2 and 3. The pulse decay is given as follows:

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

where:

α and β = dimensionless parameters given by:

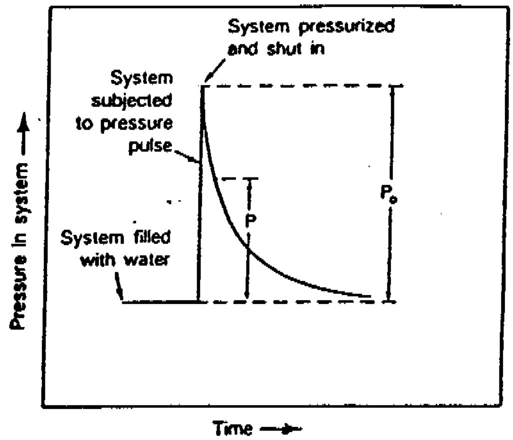

FIG. 3 Typical Pressure Record

$$\alpha = \pi r_w^2 S/V_w C_w \rho g \quad (2)$$

and

$$\beta = \beta T t/V_w C_w \rho g \quad (3)$$

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, and
S = storativity.

7.1.1 In Fig. 3, the pressure of the packed-off interval and tubing filled with water is considered constant. In those cases where the response of the system to filling is time dependent, interpretation of the pressure pulse test is unaffected, provided the time dependency is linear. Neuzil (3) has proposed a modification to the Bredehoeft and Papadopulos procedure for interpreting test data when the response of the system to filling is non-time dependent and when the compressibility of the shut-in well is significantly larger than that of water. Tables of the function $F(\alpha, \beta)$ have been provided by Cooper *et al* (4), Papadopulos (5), and Bredehoeft and Papadopulos (1).

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 $\alpha \leq 0.1$, 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

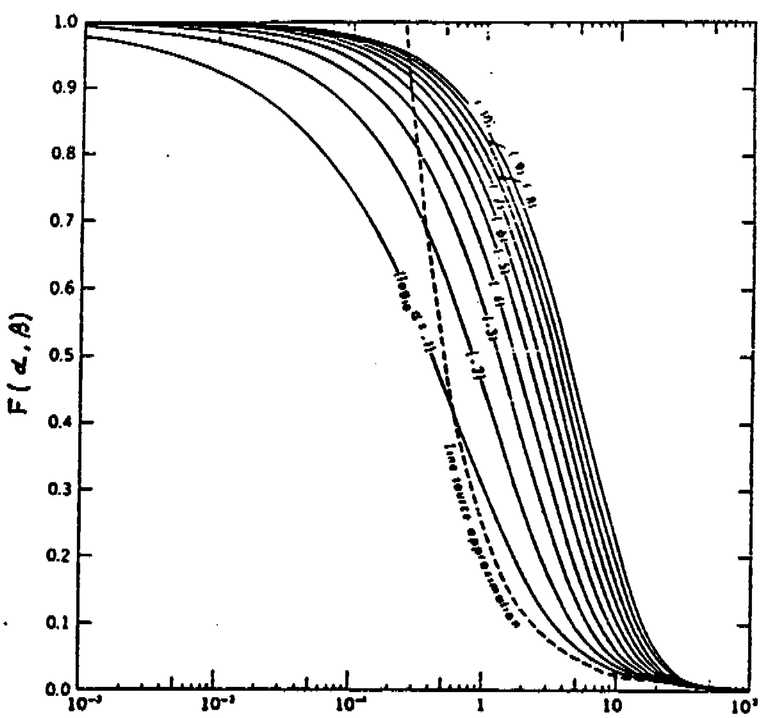

FIG. 4 Type Curves of the Function $F(\alpha, \beta)$ Against the Parameter β for Different Values of α

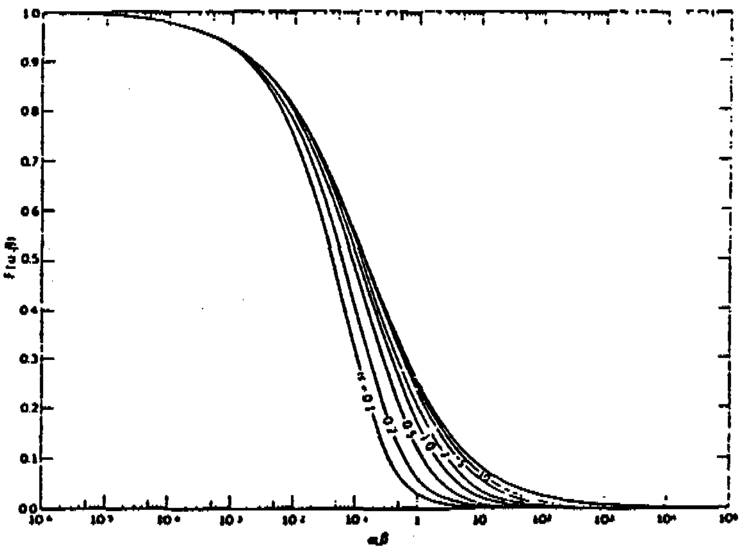

FIG. 5 Type Curves of the Function $F(\alpha, \beta)$ Against the Product Parameter $\alpha\beta$

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 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:

$$\begin{aligned}\log (e/10^6) = & -0.32 \log (t) + C \\ & + 0.32 [2 \log (r_w/0.04) \\ & + \log (2.394\mu C_w \times 10^{12})] \\ & + 0.333 \log (L/2).\end{aligned} \quad (4)$$

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 = a 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:

$$T = \rho g e^3/12\mu \quad (5)$$

Thus, Eq 5 provides transmissivity in terms of a parallel-plate equivalent fracture aperture calculated from Eq 4.

7.3.2 Eqs 4 and 5 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 The report shall include the following:

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.

8.1.1.1 *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 test matrix in tabular form.

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

8.1.1.1.3 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.

8.1.1.2 *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 the 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 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, transmissivity and storativity, and pressure pulse amplitude and decay time (or recording time, if the decay is incomplete).

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

8.1.4.4 *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.

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

9. Precision and Bias

9.1 *Error Estimmte:*

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 pressure determination, measurement of time, and type curve matching or early decay time analysis.

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

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 rock type with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

REFERENCES

(1) Bredehoeft, J. D., and Papadopulos, S. S. "A Method for Determining the Hydraulic Properties of Tight Formations," *Water Resources Research*, Vol 16, 1980, pp. 233–238.

(2) Wang, J. S. Y., Narasimhan, T. N., Tsang, C. F., and Witherspoon, P. A., "Transient Flow in Tight Fractures," *Proceedings of the 1st Invitational Well Testing Symposium*, Berkeley, 1977, pp. 103–116.

(3) Neuzil, C. E., "On Conducting the Modified 'Slug Test' in Tight Formations," *Water Resources Research*, Vol 18, 1982, pp. 439–441.

(4) Cooper, H. H., Bredehoeft, J. D., and Papadopulos, S. S., "Response of a Finite Diameter Well to an Instantaneous Charge of Water," *Water Resources Research*, Vol 3, 1967, pp. 263–269.

(5) Papadopulos, S. S., Bredehoeft, J. D., and Cooper, H. H., "On the Analysis of 'Slug Test' Data," *Water Resources Research*, Vol 9, 1973, pp. 1087–1089.

(6) Doe, T. W., Long, J. C. S., Endo, H. K., and Wilson, C. R., "Approaches to Evaluating the Permeability and Porosity of Fractured Rock Masses," *Proceedings of the 23rd U.S. Symposium on Rock Mechanics*, Berkeley, 1982, pp. 30–38.

(7) Earlougher, R. C., "Advances in Well Test Analysis," *Society of Petroleum Engineers of AIME*, New York, NY, 1977.

(8) Freeze, R. A., and Cherry, J. A., *Groundwater*, Prentice-Hall, Englewood Cliffs, NJ, 1979.

(9) Shuri, F. S., Feves, M. L., Peterson, G. L., Foster, K. M., and Kienle, C. F., Public Draft: "Field and In Situ Rock Mechanics Testing Manual," Office of Nuclear Waste Isolation, Document ONWI-310, Section F: "In Situ Fluid Properties," GT-F.1 In Situ Permeability Measurement of Rock Using Borehole Packers, 1981.

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