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## 1.0 SCOPE AND APPLICATION

The purpose of this Standard Operating Procedure (SOP) is to present a guide for conducting packer testing in fractured bedrock boreholes or the uncased intervals of bedrock monitoring wells. These are single-hole tests used to characterize significant flowing fractures or contaminant plume geometry in a bedrock aquifer. They provide data for delineating and predicting contaminant transport in the fractured bedrock aquifer at a site.

A Quality Assurance Project Plan (QAPP) in Uniform Federal Policy (UFP) format describing the project objectives must be prepared prior to deploying for a sampling event. The sampler needs to ensure that the methods used are adequate to satisfy the data quality objectives listed in the UFP-QAPP for a particular site.

The procedures in this SOP may be varied or changed as required, dependent on site conditions, equipment limitations or other procedural limitations. In all such instances, the procedures employed must be documented on a Field Change Form and attached to the QAPP. These changes must be documented in the final deliverable.

## 2.0 METHOD SUMMARY

Packer testing involves isolating a portion of a bedrock borehole or well by sealing a water-bearing zone with an inflatable packer or packers so that hydraulic conductivity testing (pumping test, Lugeon test, constant-pressure injection test, constant-rate injection test, pressure-pulse test and slug test) can be performed or groundwater samples can be collected. A series of such tests and samples enables the hydraulic conductivity and water quality to be vertically defined in the saturated interval of the borehole or well. Hydraulic and chemical data collected from several boreholes can be interpreted to conceptualize the groundwater movement and contaminant transport in the bedrock aquifer at a site.

A borehole is developed and water level and total well depth measurements are collected. The packer assemblies are then lowered to the required depth(s). If possible, testing/sampling progresses from the least contaminated well to the most contaminated well.

## 3.0 SAMPLE PRESERVATION, CONTAINERS, HANDLING, AND STORAGE

Section not applicable to this SOP.

## 4.0 INTERFERENCES AND POTENTIAL PROBLEMS

### 4.1 Hydraulic Conductivity Testing

#### 4.1.1 Pumping Test

Refer to Environmental Response Team (ERT) SOP, *Controlled Pumping Test*, for interferences and potential problems associated with pumping tests.

#### 4.1.2 Lugeon Test

- Leaks from the supply line or past the packer(s) will have the effect of apparently increasing the permeability of the test zone. Packer bypass leakage can be detected using pressure transducers placed above and below the test interval. A rise in head detected by the transducers may indicate leakage from the test section. Increasing the packer pressure should bring flow back to a linear relationship with pressure if packer leakage is occurring between the packer bladder and borehole wall. This will not prevent leakage through fractures that intersect the test interval and also intersect fractures connected to the borehole wall above or below the test zone. Adjusting the length of the test interval may prevent the fracture leakage. However, leakage through the matrix rock if it has significant permeability cannot be prevented.

- Head loss due to friction in the supply line during the testing should be accounted for in the permeability calculation. The head loss can be compensated for using a transducer placed in the test zone; otherwise, it can be estimated using a pipe flow curve if pressure is measured using a gauge at the ground surface.

- Single-well hydraulic testing does not allow for determination of the coefficient of storage.

- Care must be taken to ensure flow is laminar and that jacking or hydrofracturing are not occurring during the test. Fracture washout and plugging can also affect the test results.

- Spatial resolution of the permeability data is dependent on the length of the test interval or the packer spacing.

4.1.3 Constant-Pressure Injection Test

- Care must be taken not to use pressures that produce fracture dilation or hydrofracturing.

- Packer bypass leakage and short-circuiting will affect the test results.

4.1.4 Constant-Rate Injection Test

- Care must be taken to ensure flow is laminar and that jacking or hydrofracturing are not occurring during the test. Fracture washout and plugging can also affect the test results.

- Packer bypass leakage and short-circuiting will affect the test results.

4.1.5 Pressure-Pulse and Slug Tests

- Care must be taken not to use pressures that produce fracture dilation or hydrofracturing.

4.2 Groundwater Sampling

- Packer bypass leakage and the potential for cross contamination due to vertical groundwater flow if the packers are removed from the borehole are the main problems.

- Some specialized training may be required for collecting the groundwater samples.

## 5.0 EQUIPMENT/APPARATUS

### 5.1 Packer Assemblies

A packer consists of a mandrel (hollow-steel pipe) with a non-, partially-, or fully-reinforced rubber element on the outside that is fixed at one or both ends of the mandrel. Fixed-end packers are well suited to cased-borehole applications; whereas, moving-end packers are well suited for open-borehole applications. When inflated inside the borehole, the packer forms a seal against the borehole wall. The mandrel allows access to the isolated portion of the borehole.

One packer in an open borehole can isolate an interval extending from the packer to the bottom of the borehole. Two packers separated by a length (typically 10 feet or more) of perforated pipe can isolate an interval at a specific depth in a borehole or the open interval of a well. Multiple packers can be combined to isolate several zones in a borehole or well. In general, the largest diameter packer that can be run based on the borehole size should be selected for use because the pressure rating of the packer will have to be much higher if it must expand an appreciable percentage of its deflated diameter before reaching the borehole wall.

### 5.2 Inflation Fluids and Pressures

Most packers are designed to be inflated with either gas or liquid using appropriate tubing or piping that extends from the packer to the surface. Inflation pressure must be added to the hydrostatic pressure (1 foot water equals 0.43 pounds per square inch [psi]) and the anticipated differential pressure at the packer depth to ensure that enough pressure has been applied to pneumatically inflate, seat, and secure the packer. A regulator is used to control inflation pressure inside a gas-filled packer. If the packer is hydraulically inflated, the pressure at the pump must be equal to the inflation pressure plus the hydrostatic friction loss (between liquid and pipe wall) and differential pressures. Never exceed the maximum inflation pressure for a packer. It should be verified that the packer is maintaining pressure following inflation by monitoring a pressure gauge connected to the inflation line at the surface.

Pressure transducers are connected to the packer assembly to monitor the integrity of the packer seal and to assess short-circuiting past the packers following inflation. Transducers are located along the packer assembly at points above, within, and below (if possible) the targeted zone. Transducer readings are allowed to stabilize in the monitored zones following packer inflation. Changes in pressure at points above and below the isolated zone indicate leakage past the packers during testing or sampling.

### 5.3 Hydraulic Conductivity Testing

Standard equipment for hydraulic testing of fractured rock includes:

- Appropriate air monitoring equipment [photoionization detector (PID) and/or flame ionization detector (FID)]
- Clean water supply, flowmeter with data logger, and flow control valve
- Injection line or riser pipe
- Generator
- Packer assembly, inflation tubing, and support cable

- Compressed gas and regulator or hydraulic pump and pressure gauge for packer inflation
- Service rig or tripod and winch
- Pressure transducers with internal data loggers and cables
- Portable computer or handheld device with data download cable and software
- Electric water level indicator, marked in increments of 0.01-foot
- Site logbook, personal logbook, and/or field data sheets
- Keys to well and access gate(s) where necessary, and
- Decontamination supplies

Specific equipment required for the different types of hydraulic conductivity tests are listed in the subsections below.

5.3.1 Pumping Tests

- Refer to ERT SOP, *Controlled Pumping Test*, for additional equipment required to conduct pumping tests.

5.3.2 Lugeon Tests

- Progressive, cavity-type, positive displacement pump and water supply. Flowrate is measured using a magnetic flowmeter.

5.3.3 Constant-Pressure Injection Tests

- Due to the difficulty of monitoring a constant pump pressure, pressure tanks fitted with regulators are often used to conduct constant-pressure tests.

- Remotely controlled downhole valve located above or in the test interval.

5.3.4 Constant-Rate Injection Tests

- Remotely controlled downhole valve located above or in the test interval.

5.3.5 Pressure-Pulse and Slug Tests

- Remotely controlled downhole valve located above or in the test interval.

5.4 Groundwater Sampling

Refer to ERT SOP, *Groundwater Well Sampling,* for sampling equipment.

## 6.0 REAGENTS

No chemical reagents are used for this procedure; however, decontamination solutions may be necessary. If decontamination of equipment is required, refer to ERT SOP, *Sampling Equipment Decontamination* and the site-specific UFP-QAPP.

7.0 PROCEDURES

7.1 Field Preparation

1. Determine the number of tests to be conducted, the methods to be employed, and the equipment and supplies needed.

2. Decontaminate or pre-clean equipment as per ERT SOP, *Sampling Equipment Decontamination*, and ensure that it is in working order.

3. Coordinate the hydraulic conductivity testing or groundwater sampling schedule with staff, property owner, and regulatory agency, if appropriate.

4. The bedrock borehole should be properly developed prior to testing per ERT SOP, *Monitoring Well Development*.

5. If this is an initial visit, perform a general site survey prior to site entry in accordance with the current approved site specific Health and Safety Plan (HASP).

6. Identify test well location(s) and review well construction details.

7.2 Pre-Test Water Level and Total Well Depth Measurement

1. If possible, and when applicable, test those wells that are least contaminated and proceed to those most contaminated.

2. Remove the (locking) well cover, note the well identification (ID), the date and time of day, and the participating field personnel in the site logbook, a personal logbook, and/or on a field data sheet.

3. Remove well cap.

4. If organic contaminants are suspected, monitor the head space of the well and periodically monitor the breathing zone around the well with a PID or FID. Record the results in the site logbook, personal logbook, and/or on a field data sheet.

5. Measure a static water level in the well (ERT SOP, *Water Level Measurement*) and total well depth. Record all measurements in the site logbook, the sampler's personal log book, and/or on field data sheets. NOTE: All data recorded in a personal log book must be photocopied and retained in the project files.

6. Decontaminate the water level measurement equipment as outlined in Step 2 of Section 7.1 (above), and store for transport to the next test location.

7.3 Deployment of Packer Assemblies

Packer assemblies are lowered down the borehole using a wireline or riser pipe. Leak testing of the packer assembly within a steel casing in the upper portion of the borehole is recommended before deployment. Variations in the borehole diameter with depth should be determined using a caliper logger to avoid placing the packers within rough sections of the borehole wall where they may be punctured during inflation. It is also useful to have confirmed the locations of fractures along the borehole by using a heat-pulse flowmeter or other downhole geophysical tools and by examining the core. Knowledge of the fracture locations is used to design the length of the packer assembly and to select the intervals where hydraulic testing and groundwater sampling will be conducted. The borehole should be developed before the packer assembly is installed to ensure drilling fluids and cuttings have been removed from the test interval(s).

Single-packer assemblies are typically used while the borehole is being advanced. The bottom section of the borehole is successively isolated for testing or sampling after drilling to desired depths. The drill string and packer assembly have to be raised and lowered for each advance of the borehole. Therefore, this method of deployment usually disrupts drilling progress. An alternative approach is to deploy a double-packer assembly after all drilling activities have been completed, progressing from the bottom to the top during subsequent testing or sampling of the borehole.

7.4 Hydraulic Conductivity Tests

There are three categories of test methods for determining the hydraulic conductivity of fractured rock in a single borehole that has been isolated using packers:

- **Pumping tests for high hydraulic conductivity (>$10^{-3}$ centimeters per second [cm/s]).** Refer to ERT SOP, *Controlled Pumping Tests*, for pumping test procedures. Although not all of the fundamental assumptions (i.e., homogeneous, isotropic, and continuous aquifer) applicable to pumping tests in unconsolidated porous media are met, those analytical concepts are still applicable to many pumping tests in fractured rock enabling radial porous flow equations to be used for calculating the transmissive and storage characteristics of the aquifer.

- **Lugeon tests for moderate hydraulic conductivity ($10^{-3}$ to $10^{-8}$ cm/s).** Standard pumping tests are not appropriate for moderate to low hydraulic conductivity fracture zones because they rapidly dewater the borehole. To avoid this occurrence, a low pumping rate has to be used, but controlling it becomes technically difficult. In addition, well bore storage masks the aquifer response in the early-time data and the pumping test has to be extended a significant period to sufficiently define the shape of the type curve. In such a case, the hydraulic conductivity of the borehole section can be estimated using a Lugeon test. The test involves injecting a relatively small volume of clean water into the packed-off interval. Quasi-steady state flow rates over a range of constant pressures are recorded during the test. Injection flow rate and the head change in the test interval are monitored with a datalogger connected to an electromagnetic flowmeter and pressure transducer, respectively. The pressure applied on the test interval can also be measured using a gauge installed at a known height above the ground surface. Intervals of interest along the borehole length are tested using either a single or a double packer assembly. A minimum of three pressure increases (0.5 $P_{max}$, 0.75 $P_{max}$, and $P_{max}$) followed by a minimum of two pressure decreases (0.75 $P_{max}$ and 0.5 $P_{max}$) are typically used during the testing. Where:

$$P_{max} = \text{Depth (feet)} \times 1 \text{ psi/foot}$$

In general, each of the pressures should be maintained until a uniform rate of flow is attained for 5 to 10 minutes. During the execution of each stage, both the water pressure (P) and flow rate (Q) are regularly recorded (typically every minute). Average values for P and Q are used to calculate the hydraulic conductivity for each stage of the test. The hydraulic conductivity can be stated in Lugeon units which are defined as the hydraulic conductivity required for a flow rate of 1 Liter per minute per meter of the test interval under an effective pressure of 1 mega Pascal (MPa). Under homogeneous and isotropic conditions, 1 Lugeon is equal to 1.3 x $10^{-7}$ meters/second (Fell *et. al.*, 2005). Hydraulic conductivity can also be calculated in cm/s using industry standard equations.

The results of a Lugeon test are plotted with the effective pressure applied on a test interval. The set of Lugeon data will exhibit a pattern that can be used to interpret the flow behavior during the test. Five types of flow behavior are usually observed:

1. Laminar flow with all Lugeon values approximately equal regardless of the water pressure.
2. Turbulent flow with Lugeon values decreasing as the water pressure increases.
3. Dilation flow with the Lugeon values varying proportionally to the water pressures and the maximum Lugeon value occurring at the stage with the maximum water pressure.
4. Wash out flow with the Lugeon values increasing as the test progresses.
5. Void filling flow with the Lugeon values decreasing as the test proceeds.

- **Slug tests for low hydraulic conductivity (<$10^{-8}$ to $10^{-11}$ cm/s) fracture systems.** Characterization of low hydraulic conductivity bedrock can be performed using slug tests. Water is either added (for a slug-injection test) or removed (for a slug-withdrawal test) from the pipe string to a desired level while the shut-in valve is closed. The shut-off valve is then quickly opened after an equilibration period. The tubing radius and fluid density determine the resulting pressure change for a given amount of fluid that entered or exited the tested interval. The pipe string radius must be known to estimate the hydraulic conductivity from a slug-test response.

- **Specialized tests for very low hydraulic conductivity (<$10^{-11}$ cm/s) fracture systems.** These tests require highly sensitive and precise equipment. Equipment calibration and use in the field become extremely important in obtaining accurate data.

  A. Constant-pressure injection tests are generally conducted as follows:

     1. The packer assembly is lowered to the desired test depth.

     2. The packers are inflated and the system is filled with water to ensure that air bubbles are not trapped in the tubing and packer interval. If a down-hole valve is located within or above the test interval, the valve is closed and the packer interval is monitored until it stabilizes at the hydrostatic pressure.

     3. The injection line is pressurized to the preselected constant pressure (typically between 50 to 100 psi above the stabilized pressure) and the

valve is opened to initiate the test.

4. Constant pressure is maintained and the flow rate is recorded for a typical period of 15 minutes to 2 hours.

5. The pressure is then released and the test section is monitored until a reasonable level of recovery has occurred (typically 70 percent [%] of the stabilized pre-test pressure).

B. Constant-rate injection tests are typically performed as follows:

1. The packer assembly is lowered to the desired test depth.

2. The packers are inflated and the system is filled with water to ensure that air bubbles are not trapped in the tubing and packer interval. If a down-hole valve is located within or above the test interval, the valve is closed and the packer interval is monitored until it stabilizes at the hydrostatic pressure.

3. The downhole valve is opened and water is injected at a constant rate into the packer interval.

4. Transient pressure in the packer zone is monitored during injection for a period of up to 3 hours.

5. The pressure recovery response may also be monitored following injection until a reasonable level of recovery has occurred (typically 70 % of the stabilized pre-test pressure).

C. A pressure-pulse test is similar to a slug test but provides results more rapidly because head recovery is controlled by compressibility effects rather than the filling or draining of water from the pipe string. Pressure-pulse tests are typically conducted as follows:

1. The packer assembly is lowered to the desired test depth.

2. The packers are inflated and the system is filled with water to ensure that air bubbles are not trapped in the tubing and packer interval.

3. The downhole valve is closed and the pressure is monitored until it equilibrates at hydrostatic.

4. When the pressure stabilizes, the hydraulic head in the injection line is raised 50 to 100 psi above the hydrostatic pressure in the test interval.

5. The downhole valve is opened just long enough for the head in the injection line to be transmitted to the test interval. The pressure decay in the packer interval is subsequently monitored over time.

6. The duration of the test depends on the transmissivity of the test interval and compressibility of the groundwater. The test should continue until the pressure in the test zone has recovered to at least 70% of the stable pretest level.

D. A slug test is performed by quickly raising or lowering the water level in the pipe string connected to the test interval and monitoring its recovery to a stable value. Slug tests are typically conducted as follows:

1. The packer assembly is lowered to the desired test depth.

2. The packers are inflated and the downhole valve is closed to stabilize the pressure.

3. The water level in the pipe string connected to the test interval is raised or lowered by the addition or removal of water.

4. The downhole valve is opened allowing the head in the pipe string to be transmitted to the test interval.

5. The duration of the test depends on the transmissivity of the test interval and the inside diameter of the pipe string. Lower transmissivities and larger diameter pipes result in longer test times. The test should continue until the pressure in the test zone has recovered to at least 80% of the stable pretest level.

6. For more information on Slug Tests, please see ERT SOP, *Slug Tests*.

7.5 Hydraulic Conductivity Test Procedures

1. Cover sharp edges of the well casing with duct tape to protect the transducer cable and packer inflation tubing.

2. Program the data logger(s) for collecting and recording the water pressure and flow rate data.

3. Install the test assembly and riser or injection pipe in the borehole and seal the packer assembly against the borehole wall. Connect in-line flow meter or pressure gauge to the supply pipe.

4. Allow the water level in the test zone to re-equilibrate and measure the equilibrated water level in that interval. Record the measurement in the site logbook, personal logbook, and/or on a field data sheet.

5. At a predetermined time zero, initiate the test following the appropriate procedures presented in Section 7.4.

6. Continue the test until drawdown or recovery has reached a predetermined value.

7. Stop the logging sequence when using a data logger and download the data from the logger to a portable computer.

8. Deflate the packer assembly and move it to the next test interval.

9. Decontaminate and dispose of equipment as per ERT SOP, *Sampling Equipment Decontamination*.

10. Review field forms for completeness.

7.6 Groundwater Sampling

Open boreholes tend to provide groundwater samples that average the contaminant concentrations over the zone of investigation. Groundwater sampling using packers enables discrete samples and water level measurements to be collected from selected intervals. A single or double packer and pump combination may be used for obtaining groundwater samples from a single interval. Refer to ERT SOP, *Groundwater Well Sampling*, for groundwater sampling procedures.

Multi-level sampling is also possible using a series of intake ports separated by inflatable packers all on a single casing string. Such packer assemblies are usually a permanent installation. All of the packers and sample ports are connected to the surface by tubing or are accessible from the surface using portable probes and tools. Samples are typically collected after purging using bladder pumps or without purging using formation pressure. Currently available multi-level monitoring systems utilizing packers include: Westbay MP®, Waterloo™, Solinst CMT™, and Barcad.

7.7 Groundwater Sampling Procedures

1. Install the packer assembly, pump, and riser pipe in the borehole and seal the packer assembly against the borehole wall.

2. Refer to ERT SOP, *Groundwater Well Sampling,* for purging and sampling of bedrock boreholes and open-intervals of bedrock monitoring wells.

3. Deflate the packer assembly and move it to the next test interval or remove it from the borehole after the sampling is completed.

4. Decontaminate and dispose of equipment as per ERT SOP, *Sampling Equipment Decontamination* after all intervals have been sampled and the packer assembly has been removed from the borehole.

## 8.0 CALCULATIONS

8.1 Pumping Tests

Refer to ERT SOP, *Controlled Pumping Test*, for calculation procedures.

8.2 Lugeon Tests

The Lugeon value for each stage of a test is calculated as follows:

$$\text{Lugeon Value} = (Q/L) \times (P_o/P)$$

Where,

$Q$ = flow rate (Liters/minute),
$L$ = test interval length (meters),
$P_o$ = reference pressure of 1 MPa, and
$P$ = test pressure in MPa

The hydraulic conductivity for each stage of the test can be calculated using the following equation from Canada Centre for Mineral and Energy Technology (Canmet 1977):

$$k = 5.833/(\pi L)(Q/H)(10^{-5})$$

Where,

$k$ = hydraulic conductivity (meters/second),
$Q$ = flow rate (Liters/minute),
$L$ = test interval length (meters), and
$H$ = pressure head at center of test section (meters of water)

8.3 Constant-Pressure Injection Tests

The simplest method of analysis involves plotting shut-in pressure ($P_{si}$) divided by discharge rate ($Q$) versus the logarithm of elapsed time ($t$) since the valve was opened. Selecting the change ($\Delta$) in $P_{si}/Q$ over one log-cycle of $t$ simplifies the transmissivity equation (Jacob and Lohman, 1952) from:

$$T = 2.30/4\pi[\Delta(P_{si}/Q)/\log_{10}t] \quad \textit{to} \quad T = 0.183/\Delta(P_{si}/Q)$$

8.4 Constant-Rate Injection Tests

Data for constant-rate injection tests can be analyzed in the same manner as constant-pressure tests utilizing the following plots of pressure ($p$) and time ($t$):

- Type curve matching using log-log plots of $p$ versus $t$,
- Plot of $p$ and log $t$,
- Plot of $p$ and square root $t$, and
- Plot of $p$ and fourth root $t$.

8.5 Pressure-Pulse Injection Tests

Data for pressure-pulse injection tests can be analyzed by matching type curves (Bredehoeft and Papadapoulos, 1980 and Wang *et. al*., 1978).

8.6 Slug Tests

Slug test data are typically analyzed using semilog plots of hydraulic head or pressure versus time (Bouwer and Rice, 1976 or Hvorslev, 1951). The alternative approach is a type curve analysis based on a log-log plot of hydraulic head or pressure versus time (Cooper *et. al.*, 1967).

## 9.0 QUALITY ASSURANCE/QUALITY CONTROL

There are no specific quality assurance (QA) activities which apply to the implementation of these procedures. However, the following general QA procedures apply:

1. All data must be documented on field data sheets or within site logbooks.
2. All equipment and instrumentation must be operated in accordance with operating instructions as supplied by the manufacturer, unless otherwise specified in the site-specific UFP QAPP.

## 10.0 DATA VALIDATION

Data verification/completeness checks must be conducted to ensure project-specific quality objectives have been met as defined in the corresponding UFP-QAPP. The contractor's Task Leader is responsible for completing the UFP-QAPP verification checklist for each project.

## 11.0 HEALTH AND SAFETY

Based on Occupational Safety and Health Administration (OSHA) requirements, a site-specific health and safety plan (HASP) must be prepared for response operations under the Hazardous Waste Operations and Emergency Response (HAZWOPER) standard, 29 CFR 1910.120. Field personnel working for EPA's ERT should consult the Emergency Responder Health and Safety Manual currently located at https://response.epa.gov/_HealthSafetyManual/manual-index.htm for the development of the HASP, required personal protective equipment (PPE) and respiratory protection.

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## 13.0 APPENDICES

This section is not applicable to this SOP.