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HYDRAULIC TESTING OF PALEOZOIC AND PRECAMBRIAN STRATA AT THE BRUCE SITE

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ABSTRACT

Straddle-packer hydraulic testing is being performed in boreholes DGR-1 and DGR-2 at the Bruce site near Tiverton, Ontario, Canada, as part of the Geoscientific Site Characterization Program for a proposed deep geologic repository for low- and intermediate-level radioactive waste. The purpose of the testing is to provide hydraulic conductivity and head information that can be used to model groundwater flow at the Bruce site. Slug tests and drillstem tests are being performed in the Silurian strata in DGR-1, and pulse tests are planned for the Ordovician, Cambrian, and Precambrian strata in DGR-2.

RÉSUMÉ

Les tests hydrauliques entre double obturateur sont réalisés dans les forages DGR-1 et DGR-2 au site de Bruce près de Tiverton, Ontario, Canada, dans le cadre du programme géoscientifique de caractérisation d'un site pour un stockage géologique profond proposé pour des déchets radioactifs de bas et de moyenne activité. Le but des tests est de fournir les informations de perméabilité et de charge hydraulique qu'on peut employer pour modeler l'écoulement d'eau souterraine au site de Bruce. Les slug tests et les drillstem tests sont réalisés dans les strates siluriennes dans DGR-1, et les pulse tests sont planifiés pour les strates d'ordovician, cambriennes, et précambriennes dans DGR-2.

1 INTRODUCTION

Straddle-packer hydraulic testing is being performed in Silurian, Ordovician, Cambrian, and Precambrian strata in boreholes DGR-1 and DGR-2 at the Bruce site near Tiverton, Ontario, Canada, as part of the Geoscientific Site Characterization Program for a proposed deep geologic repository for low- and intermediate-level radioactive waste (Intera Engineering Ltd. 2006). The purpose of the testing is to provide hydraulic conductivity and head information that can be used to model groundwater flow at the Bruce site. The testing is being performed using a custom-built straddle-packer tool that incorporates features from oilfield straddle-packer tools previously used at the Waste Isolation Pilot Plant (WIPP) and other radioactive waste repository sites, as well as innovative downhole shut-in valves and a piston pulse generator.

2 TEST BOREHOLES AND INTERVALS

DGR-1 was cored to the top of the Upper Ordovician Queenston shale to an approximate depth of 463 m below ground surface (bgs). DGR-2 was rotary drilled and cased to the top of the Queenston, and then cored to an approximate depth of 850 m bgs, ~15 m into the Precambrian. Both holes were cored at a 152-mm diameter. Intervals were selected for testing on the basis of core, geophysical logs, and fluid electrical conductivity (FEC) logging (Beauheim and Pedler 2007) with the goal of testing the most permeable horizons in each formation or member as well as more typical horizons.

The intervals selected for testing in DGR-1 are shown in Table 1 and the general stratigraphy is shown in Figure 1. The formations to be tested in DGR-2 are shown in Table 2.

Table 1. DGR-1 test intervals.

Formation/ Member	Interval (to be) Tested (m bgs)	Tests (to be) Performed
Salina F	200-210	DST
Salina E	230-240	DST
Salina B-C	260-270	DST
Salina A2	320-332	slug
Salina A1	350-360	DST
Guelph & Amabel	372-385	slug
Fossil Hill	403-407	slug
Cabot Head	411-417	slug
Manitoulin	442-450	slug

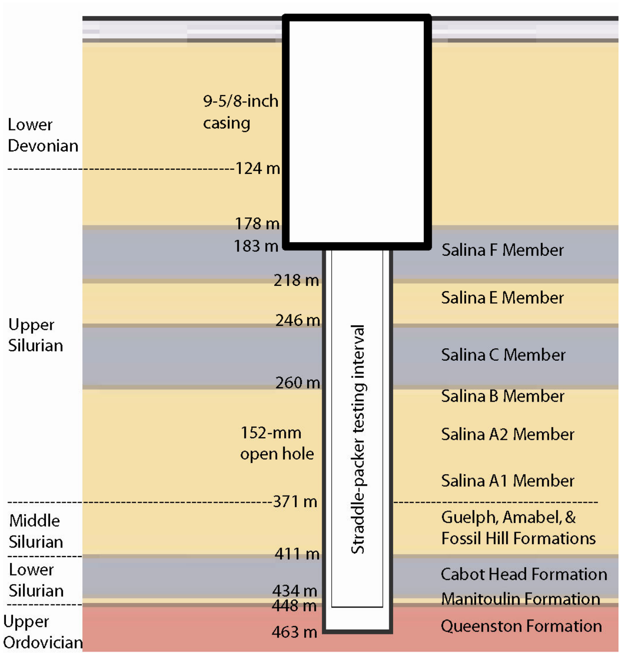

Figure 1. Stratigraphy and straddle-packer testing interval in DGR-1 (all stratigraphic depths are preliminary).

Table 2. Formations to be tested in DGR-2.

Formation(s)	Tests (to be) Performed
Queenston	pulse
Georgian Bay	pulse
Blue Mountain	pulse
Cobourg	pulse
Sherman Fall	pulse
Kirkfield and Coboconk	pulse
Gull River	pulse
Shadow Lake and Cambrian	pulse
Precambrian	pulse

3 STRADDLE-PACKER TEST TOOL

The straddle-packer test tool consists of two inflatable packers, a downhole shut-in valve, a piston-pulse tool (for DGR-2 only), a perforated section, volume-displacement sections, and miscellaneous subs and pass-throughs to connect the various pieces. The standard straddle interval is 11.6 m, although other intervals may be used when appropriate.

3.1 Packers

TAM International external-inflate sliding-end packers are used in the straddle tool. The packers have an un-inflated diameter of 10.8 cm and an element length of 1.83 m, providing a seal length of approximately 1.68 m in a 152-mm-diameter hole. They are capable of withstanding differential pressures of up to 20.7 MPa. The packers are inflated in unison with compressed nitrogen through a single 6.35-mm stainless steel line to between 3.5 and 7.0 MPa above the hydrostatic pressure at the depth of the tool. The packers are oriented so that their fixed ends are up and their sliding ends are down to avoid putting their inflation lines in tension.

3.2 Shut-In Tools

A downhole shut-in tool is used to control the connection between the interior of the tubing string above the straddle tool and the test zone between the inflatable packers. The downhole shut-in tool uses a piston-actuated ball valve to open and close the tool. The valve is set up in a normally open position and hydraulic pressure is applied to push an annular piston down, rotating the ball 90° and closing the valve. A spring pushes the piston up, opening the valve, when the hydraulic pressure is relieved. The ball has a 1.27-cm-diameter opening, and causes no displacement in the test interval when it is actuated.

Two solenoid-actuated coaxial shut-in valves will also be available for the testing at the Bruce site. One of the valves is normally open and the other is normally closed. A spring maintains the valve position in its normal state, open or closed depending on model. The solenoid shifts the valve position when a 24-volt 1.5-amp current is applied to the valve. The valve is driven by an AC-to-DC 0-100 volts power supply. The output voltage of the power supply is calculated based on the drive-cable length and gauge.

Normally open tools are better suited to slug tests, in which the tool needs to remain open after the test has been initiated, whereas normally closed tools are better suited to pulse tests, in which the tool needs to remain closed after the test has been initiated. A normally closed tool is more appropriate for DSTs as well, because DST buildup periods, in which the tool must be closed, are generally longer than DST flow periods, in which the tool must be open. As long as no interruptions in power occur, either type of tool can be used for all of the tests.

3.3 Piston Pulse Generators

For pulse-testing applications, a pressure pulse is created by displacing a known volume of the test zone using a hydraulically actuated piston. Several versions of the pulse generator are available with different volume displacements.

3.4 Perforated Section

One section of the tool string between the straddle packers must allow flow from the straddled test zone into the tool string. A perforated 1.22-m-long pup joint of 2.375-inch tubing is used for this purpose. The pup joint has a total of 36 6.35-mm perforations arranged in four lines down the length of the joint.

3.5 Volume-Displacement Sections

To reduce the volume of water in the test zone during pulse tests, the tool sections used to achieve the desired spacing between straddle packers have been manufactured from 3-inch stainless steel pipe rather than from 2.375-inch tubing.

4 DATA ACQUISITION

4.1 Data-Acquisition System

The Sixnet data-acquisition system (DAS) used for the straddle-packer hydraulic testing was developed by Sandia National Laboratories (SNL) for use at the Waste Isolation Pilot Plant (WIPP). The DAS is contained in SNL's Mobile Integrated Aquifer Testing and Analysis (MIATA) trailer which is being used for the testing at the Bruce site. The DAS human-machine interface (HMI) software displays the status of all parameters including the shut-in valve state, zone pressures, packer pressures, polling frequency, test start time, and test duration. The HMI also provides real-time plotting of any parameter being measured.

4.2 Pressure Transducers

Paroscientific Series 8CB High Pressure Intelligent Depth Sensors are being used to monitor pressures in all zones isolated during hydraulic tests. These transducers have a 0-1400 metres of water range of operation, which corresponds to approximately 0-14000 kPa. They have an accuracy of 0.01% of full scale (approximately 1.4 kPa). The transducers are housed in sensor carriers positioned above the top packer in the tool string. One transducer is ported to the interval below the bottom straddle packer (P1), one transducer is ported to the test zone between the packers (P2), one transducer is ported to the tubing above the shut-in valve (P3), and the fourth transducer is ported to the annulus between the tubing and borehole wall above the upper packer (P4). These pressure transducers are monitored with the DAS. The conversion from a frequency response at the gauge sensor to an engineering unit is done within the gauge.

Packer pressure is monitored with a separate pressure transducer to verify that the packers have inflated and are maintaining their pressures. Barometric pressure is monitored at 15-minute intervals during all activities with an independent barometer on the test site.

4.3 Temperature Loggers

The Paroscientific transducers described in Section 4.2 also measure temperature, which is monitored and recorded by the DAS. However, these transducers are positioned above the upper packer and do not, therefore, measure the actual temperature in the test zone or below the bottom packer. HOBO U12 Stainless Temperature Loggers are placed in the test zone and below the bottom packer to monitor temperatures in those intervals. The HOBO loggers are not connected to the DAS, but store all data internally and are downloaded whenever the test tool is brought to the surface.

5 TESTING PROCEDURES

The type of test performed in each interval is being dynamically tailored to the hydraulic conductivity of the interval in real time. Slug testing (Cooper et al. 1967; Ramey et al. 1975) is being performed in the Silurian strata in DGR-1 with hydraulic conductivities greater than ~10^{-7} m/s, drillstem tests (DSTs) (Ramey et al. 1975) are being performed in the strata with hydraulic conductivities between 10^{-10} and 10^{-7} m/s, and pulse tests (Bredehoeft and Papadopulos 1980; Neuzil 1982) will be performed in the Ordovician and Precambrian strata in DGR-2 with hydraulic conductivities <10^{-10} m/s.

To test an interval, the straddle-packer tool is lowered to the desired depth, all transducers are connected to the DAS, and data acquisition is initiated. The shut-in valve is maintained in an open position while the packers are inflated. The packers are inflated with compressed nitrogen to a pressure between 3.5 and 7.0 MPa above the hydrostatic pressure at the depth of the tool. After the packers have been inflated, the shut-in valve is closed. The test-zone pressure (P2) then typically begins to change relative to the annulus pressure (P4, which might change slowly) and the tubing pressure (P3, which should be constant) as the test-zone pressure equilibrates with the pressure of the interval to be tested. The bottom-hole pressure (P1) typically shows a pressure increase during packer inflation, and then either increases or decreases depending on the natural formation pressure in the interval isolated.

The following steps apply in DGR-1 where slug tests and drillstem tests (DSTs) are planned:

- Once a projection can be made of the likely test-zone pressure 12 hr after shut-in (within ~500 kPa), enough water is swabbed from the tubing to leave the tubing pressure (P3) ~700 kPa lower than that estimated test-zone pressure. The system is then left to stabilize for at least the balance of 12 hr after shut-in (ideally overnight).

- After 12 hr of shut-in (or the next morning), the Test Leader determines if the test-zone equilibration trend is well-enough defined to allow testing to begin, or if additional equilibration time is required. Once the Test Leader determines that testing can begin, the shut-in valve is opened to initiate a rising-head slug test.

- The Test Leader evaluates the pressure data from the test zone in real time to determine if the test should be continued as a slug test or converted to a DST. Subject to the discretion of the Test Leader, the following guidelines are used to determine if and when a slug test will be converted to a DST:

- If 30% of the initial slug has dissipated after 1 hr, the test remains a slug test.

- If 30% of the initial slug has not dissipated after 1 hr, the shut-in valve is closed and the test is converted to a DST. The time during which the shut-in valve was open constitutes the DST flow period and the time after shut-in constitutes the DST buildup period.

- Slug tests and DST buildup periods ideally continue until at least 98% pressure recovery has occurred. For a slug test, the shut-in valve is then closed and the tubing swabbed to create a pressure differential approximately half of that created for the first slug test. After the pressure disturbance caused by swabbing has dissipated, the shut-in valve is opened to begin a second slug test or DST. For a slug test converted to a DST at <30% slug dissipation, no swabbing is required before opening the shut-in valve. The second test is an exact duplicate of the first test, but with less of an initial pressure differential. Testing is terminated at any time after 98% pressure recovery has occurred or after the Test Leader has determined that the available data are adequate for analysis.

The formations to be tested in DGR-2 are expected to have hydraulic conductivities less than 1×10^{-11} m/s (Golder Associates Ltd., 2003). Consequently, more time will be required for pressure equilibration than in the higher permeability formations tested in DGR-1, and only pulse tests are likely to be performed. The following steps apply to pulse testing in DGR-2:

- The Test Leader will determine when the test-zone equilibration trend is well-enough defined to allow testing to begin, but equilibration periods of more than a day are to be expected. Particular care will be taken to identify equilibration trends that are reversing direction (e.g., initially decreasing pressure that reverses and begins to increase).

- Once the Test Leader determines that testing can begin, the piston in the piston-pulse tool will be extended to produce a pressure pulse of approximately 700 kPa (overpressure).

- The Test Leader will evaluate the pressure data from the test zone in real time to determine if the test should be continued to completion (≥98% pulse dissipation) or converted to a scoping test. A pulse test will be converted to a scoping test when nSIGHTS analysis of the real-time data indicates that the hydraulic conductivity of the tested interval cannot be determined to less than half an order of magnitude uncertainty with one week of data, but can be confidently determined to be less than 1×10^{-11} m/s.

- Pulse tests should ideally continue until at least 98% pressure recovery has occurred. Once adequate data for analysis of the first pulse test have been collected, the pulse piston will be retracted, creating an underpressure pulse of the same magnitude as the overpressure pulse used for the first test. Testing may be terminated at any time after 98% pressure recovery has occurred or after the Test Leader has determined that the available data are adequate for defensible analysis.

6 TEST ANALYSIS

The test data are being analyzed using the nSIGHTS (n-dimensional Statistical Inverse Graphical Hydraulic Test Simulator) code, which is capable of including pressure transients caused by pre-test activities in test analysis and provides an estimation of uncertainty for each inferred parameter. nSIGHTS was developed for use on hydraulic tests performed at the Waste Isolation Pilot Plant (WIPP), the United States Department of Energy (DOE) deep geologic repository for transuranic and mixed wastes. It has also been used in the Canadian, French, Swedish, Swiss, Japanese, and Taiwanese radioactive waste disposal programmes.

nSIGHTS can simulate any kind or combination of well test(s) in a single-phase system, confined or unconfined, bounded or infinite, single- or double-porosity, in fully or partially penetrating wells. Non-test events or periods can be included in the simulation by specifying pressures and/or rates. Temperature-induced changes in pressure are included by specifying the temperature measured in the borehole at each time step. nSIGHTS is unique among well-test-analysis codes in its ability to allow for any dimensionality of flow without being limited to integer dimensions (i.e., linear, radial, spherical). It provides uncertainty estimates, performs Jacobian analyses of parameter sensitivities, performs perturbation analyses to differentiate between global and local minima, and calculates correlation matrices for all parameters. In addition, it includes a full suite of visualization tools to display the many factors it can calculate.

7 TEST RESULTS

The hydraulic testing in DGR-1 is scheduled to be completed in June 2007. Testing in DGR-2 will be performed between July and September 2007. Test results will be summarized in the oral presentation of this paper.

8 SUMMARY AND CONCLUSIONS

Straddle-packer hydraulic testing is being performed in boreholes DGR-1 and DGR-2 at the Bruce site near Tiverton, Ontario, Canada, as part of the Geoscientific Site Characterization Program for a proposed deep geologic repository for low- and intermediate-level radioactive waste. The purpose of the testing is to provide hydraulic conductivity and head information that can be used to model groundwater flow at the Bruce site. The type of test performed in each interval is dynamically tailored to the hydraulic conductivity of the interval in real time. Slug testing is being performed in the Silurian strata in DGR-1 with hydraulic conductivities greater than ~10^{-7} m/s, drillstem tests (DSTs) are being performed in the strata with hydraulic conductivities between 10^{-10} and 10^{-7} m/s, and pulse tests will be performed in the Ordovician and Precambrian strata in DGR-2 with hydraulic conductivities <10^{-10} m/s.

The testing is being performed using a custom-built straddle-packer tool that incorporates features from oilfield straddle-packer tools previously used at the Waste Isolation Pilot Plant (WIPP) and other radioactive waste repository sites, as well as innovative downhole shut-in valves and a piston pulse generator. The standard straddle interval is 11.6 m, although other intervals may be used when appropriate. Intervals were selected for testing on the basis of core, geophysical logs, and fluid electrical conductivity logging with the goal of testing the most permeable horizons in each formation or member as well as more typical horizons.

The test data are being analyzed using the nSIGHTS code, which is capable of including pressure and temperature transients caused by pre-test activities in test analysis and provides an estimation of uncertainty for each inferred parameter.

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