Straddle-Packer Hydraulic Testing in Low Permeability Formations at the Site of the Proposed Deep Geologic Repository, Tiverton, Ontario: Equipment, Methodology, and Results

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Summary

The Nuclear Waste Management Organization (NWMO) is currently conducting geoscientific site characterization activities at the Bruce nuclear site in southwest Ontario to assess the suitability of the 840 m thick Paleozoic sedimentary sequence beneath the site to host a Deep Geologic Repository (DGR) for Ontario Power Generation's Low and Intermediate Level (L&ILW) radioactive waste. As part of these investigations over 100 straddle-packer hydraulic tests have been performed in deep boreholes to characterize the in-situ horizontal hydraulic conductivity of the intact rock in the Silurian and Ordovician sequences. This paper describes the design of the in-situ testing equipment, test-methodology, and analysis approach. Results of the straddle-packer testing indicate that the Ordovician rock formations that host and enclose the proposed repository are of extremely low permeability.

Introduction

Ontario Power Generation (OPG) is proposing to license and construct a DGR for L&ILW near the Western Waste Management Facility at the Bruce nuclear site near Tiverton, Ontario. As envisioned, the DGR, accessed by vertical shafts, will be comprised of a series of emplacement rooms laterally developed within the Ordovician age argillaceous limestone Cobourg Formation at a depth of about 680 m.

The site-characterization plan is described in Intera Engineering Ltd (2006, 2008). Jensen et al. (2009) provides an overview of geoscientific work programs associated with the project. A total of six deep boreholes have been drilled and cored at the site. An important component of the ongoing site characterization activities is the acquisition of estimates of rock mass hydraulic conductivity (K) through in-situ hydraulic testing. The straddle-packer hydraulic test program described in this paper was designed to acquire representative formation hydraulic conductivities for Silurian to Ordovician age sediments. Results for vertical boreholes DGR-2, DGR-3, and DGR-4 are presented in this paper. Testing in 2010 is currently underway in inclined boreholes DGR-5 and DGR-6.

Background

Straddle-packer testing uses two or more inflatable packers to isolate a section of borehole (the test interval) for testing. Originally developed to evaluate formation properties of interest to oil and gas production, the approach has also proven to be appropriate for in-situ evaluation of low-permeability media, particularly as possible host rocks for deep geologic repositories (Pickens et al. 1987. Straddle-packer equipment can be used for several types of well tests, depending upon the permeability of the formation being tested. This paper will focus on pulse testing, where the pressure response of an isolated test interval to a near-instantaneous pressure change is measured. This is the preferred approach for low permeabilities (< 10^{-11} m/s) such as those found in the Ordovician sequence at the Bruce nuclear site.

Test Equipment

Low-permeability testing is subject to non-ideal testing conditions that can have significant impact on testing results and suitability of results for analysis. The uncertainty associated with these conditions can be minimized through effective equipment design. The testing equipment used on this program was based on equipment designed to support program activities at the Waste Isolation Pilot Plant (WIPP) site in New Mexico. Improvements to equipment and test methodology were also made between each phase of activities in the current program.

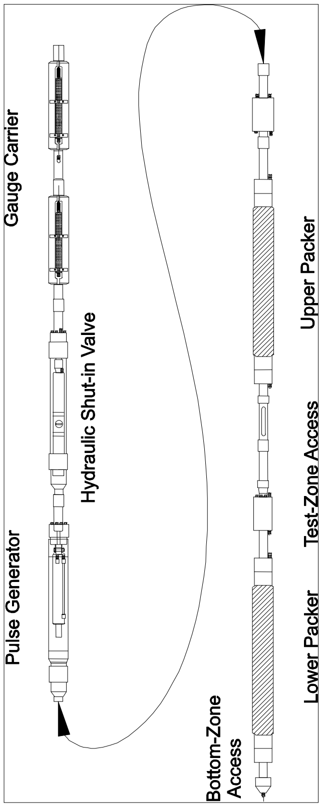

Figure 1 Downhole Equipment (not to scale)

The test equipment consists of down-hole and surface components. Down-hole equipment consists of: packers, shut-in valve, piston pulse generator, gauge carrier, and assorted feed-throughs and connecting components, as shown in Figure 1.

The packers isolate the section of formation to be tested (the test-interval). A test-interval length of approximately 30m was selected as being appropriate for determining formation scale bulk rock mass properties.

The shut-in valve separates the test interval from the tubing string. When the packers are fully inflated, closing the shut-in valve hydraulically isolates the test interval.

The piston pulse generator is a hydraulic piston mounted in a chamber connected to the test interval. In an isolated, or shut-in, test interval, extending or retracting the piston will create a near-instantaneous pressure pulse injection or withdrawal. As the volume of the piston (164 ml) and test zone is known, the size of pulse can be used to directly calculate test-zone compressibility (C_{tz}), which is a critical value for test analyses.

Pressure transducers are mounted above the shut-in valve on gauge carriers and are connected to measurement points by stainless steel lines and feed throughs. Pressure is measured in the test-zone (between the packers), the bottom-zone (below the bottom packer), the tubing above the shut-in valve, and the annulus above the top packer.

The downhole equipment is connected to surface with hydraulic lines and an armoured umbilical cable with transducer power and communication lines. The hydraulic lines and umbilical cable are clamped to the outside of a 2-3/8 inch tubing string, which provides the overall mechanical connection between a service rig at surface and the downhole tool.

Nearly all downhole equipment and components were constructed of stainless-steel. The equipment was designed with the goal of reducing test-zone compressibility to as low a value as possible. This was borne out in operation where test-zone compressibilities on the order of 4E-10 Pa^{-1} were typically measured.

With the exception of reels for the stainless steel hydraulic lines and the umbilical cable, all surface equipment is contained within a trailer-based laboratory. The laboratory is subdivided in two sections: a front section with office, computer, and Data Acquisition System (DAS) equipment; and a back section with workbench, intensifier pumps, and hydraulic line control panel. The DAS acquires data continuously from the downhole probes and additional transducers measuring barometric pressure, and pressures on each hydraulic line.

The test tool was assembled from individual components as it was lowered down the borehole. An extensive gas and liquid pressure testing program is conducted during tool assembly to eliminate leaks, which can mask the actual hydraulic response of a formation being tested. A final leak test of the assembled probe is performed after tool assembly, when a pulse test within the surface conductor casing is performed. It is worth noting that any undetected leaks within the test equipment will lead to over-estimates of hydraulic conductivity.

Test Methodology

All DGR project site characterization activities at the Bruce nuclear site are conducted under the control of a Project Quality Plan (Avis, 2009). In specific, for straddle-packer testing, the test plan describes tool assembly tests, instrumentation and data quality assurance, and the overall approach to be used in conducting each hydraulic test.

In general, test intervals were selected with slight overlap with the goal of complete coverage of the borehole. Some intervals were adjusted to attain coverage of particular formations or to examine features indicated from core logging or borehole geophysics.

The plan for a single hydraulic test consists of a stabilization period, followed by a testing period. After the test tool has been set on the specified interval, packers are inflated and the shut-in valve is closed. The interval is then allowed to stabilize to ensure that any tool-dependent compliance effects, such as packer creep, occur before testing is performed. Stabilization was determined by monitoring test-zone response and packer inflation pressures. After stabilization an initial pulse is generated. Pulse direction is based on assumed formation pressures. There was evidence that liquid pressures are significantly below hydrostatic for most of the Ordovician sequence. Consequently, pulse withdrawals were performed for most tests. In most intervals, two pulse withdrawal tests were conducted. Each pulse sequence was approximately one day in duration, with a typical total interval testing time of three days. Real time monitoring and assessment of test interval pressure transients during this period provided another measure of data reliability before interval testing was concluded.

Analysis Approach

Pressure data collected during the hydraulic tests were analyzed using the nSIGHTS (NWMP, 2006) code to estimate hydraulic conductivity and formation pressures of the tested intervals. nSIGHTS has been used in nuclear repository characterization programs around the globe, including Canada (OPG), the USA (WIPP), Sweden (SKB), France (Andra), and Japan (JNP). The code has unique capabilities that allow the analyst to incorporate complex borehole pressure histories into the simulations when estimating the hydraulic parameters and also allows for quantification of the uncertainty in the hydraulic parameter estimates. Figure 2 shows the testing sequence performed in interval DGR3_671.50-702.24 along with the best-fit nSIGHTS simulations.

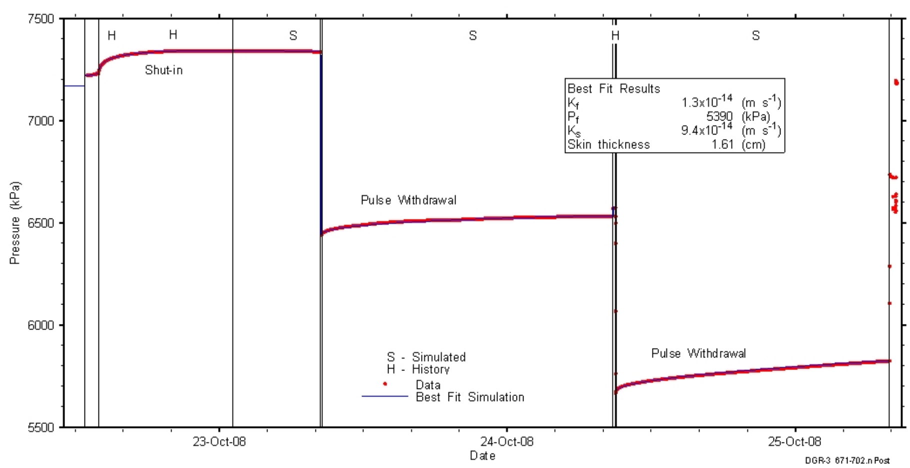

Figure 2. Annotated DGR3_671.50-702.24 testing sequence showing best fit simulation and parameter estimates.

Results

Estimates of formation or rock mass horizontal hydraulic conductivity from straddle packer testing in boreholes DGR-2, DGR-3 and DGR-4 are presented below in Figure 3. DGR-2 results are preliminary and subject to possible revision in the final analyses process. Estimated formation hydraulic conductivities have been calculated as the geometric mean of tests conducted within the formations. The results show consistent and extremely low hydraulic conductivities throughout the Ordovician shales and limestones

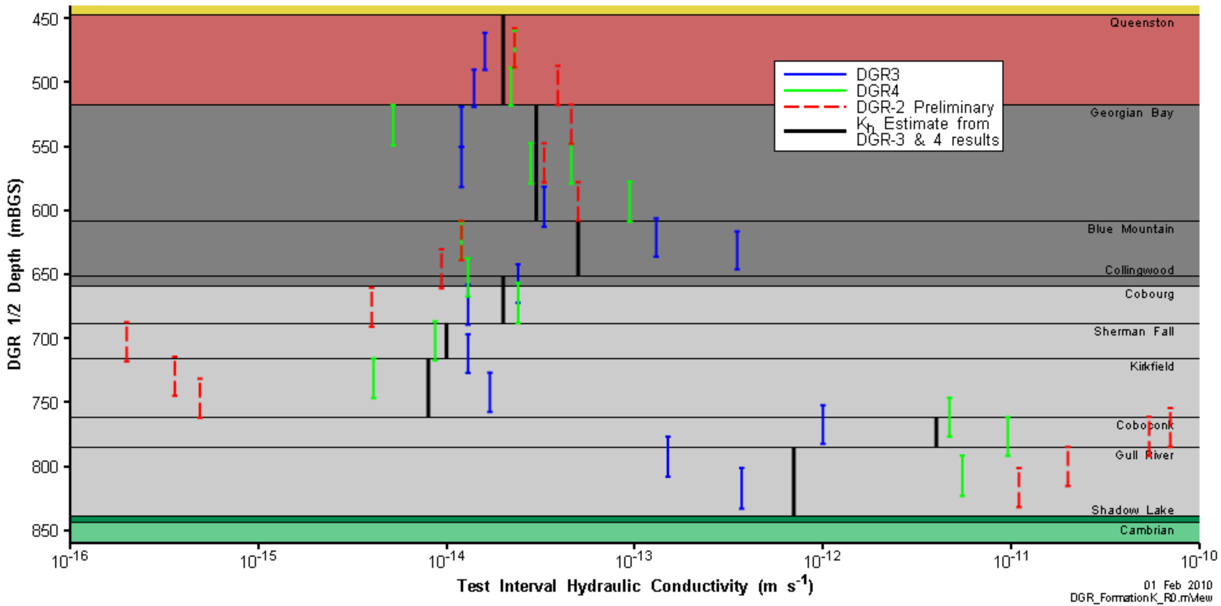

Figure 3. Summary of estimated formation hydraulic conductivity in Ordovician formations.

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Acknowledgements

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