Hydraulic testing to characterize low permeability sedimentary formations - proposed Deep Geologic Repository, Tiverton, Ontario

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ABSTRACT
On behalf of Ontario Power Generation (OPG) the Nuclear Waste Management Organization has undertaken geoscientific studies to support an Environmental Assessment process related to the proposed development of a Deep Geologic Repository (DGR) for long-term management of Low and Intermediate Level Radioactive Waste (L&ILW) generated at OPG owned facilities at the Bruce site located near, Tiverton, Ontario, 225 km northwest of Toronto. As part of these studies straddle-packer hydraulic testing has been conducted in multiple deep boreholes to characterize formation hydraulic conductivities within the 840 m thick Paleozoic age sedimentary sequence underlying the site. This paper describes the design of custom testing equipment, test-methodology, and analysis approach. Preliminary results are presented describing extremely low-permeability and underpressured formations within the Ordovician sedimentary bedrock sequence that will host and overlie the proposed DGR.

RÉSUMÉ
Au nom d'Ontario Power Generation (OPG), le Société de Gestion des Déchets Nucléaires a entrepris des études géoscientifiques pour supporter un processus d'analyse environnementale liée au développement envisagé d'un stockage en couches géologiques profondes pour la gestion à long terme de déchets de faible activité et de moyenne activité, produits aux sites qui appartiennent à OPG, au site Bruce situé près de Tiverton, Ontario, à 225 km au nord-ouest de Toronto. Dans le cadre de ces études, on a entrepris les tests hydrauliques avec un packer d'intervalles en plusieurs trous de forage profonds pour caractériser les conductivités hydrauliques des formations dedans la séquence sédimentaire de 840 m d'épaisseur qui sous-tend le site. Cet article décrit la conception des instruments d'essai fait sur commande, la méthodologie d'essai, et l'approach d'analyse. On présente des résultats préliminaires pour des formations à perméabilité extrêmement faible et à sous-pression dedans la séquence de soubassement sédimentaire ordovicien qui contiendra et qui sera au dessus du stockage envisagé.

1 INTRODUCTION

Ontario Power Generation (OPG) is proposing to construct a Deep Geologic Repository (DGR) for Low and Intermediate Level Waste (L&ILW) near the Western Waste Management Facility at the Bruce site in the Municipality of Kincardine, Ontario.

As currently envisioned, the DGR would be constructed as an engineered facility comprising a series of underground emplacement rooms at a depth of about 680 m below ground surface within the Ordovician age argillaceous limestone Cobourg Formation.

Characterization activities at the site are ongoing, and are being performed to meet the requirements specified in Geoscientific Site Characterization Plan (GSCP) (Intera Engineering, 2006, 2008). The GSCP is a multi-phase, multi-year program plan designed to allow iterative development, testing and refinement of a site-specific Descriptive Geosphere Site Model(s) (DGSM). In the first phase of the GSCP, two boreholes, DGR-1 and DGR-2, were drilled and cored through the entire sedimentary sequence underlying the Bruce site. DGR-1 was drilled and cored to the top of the Ordovician formations, while DGR-2 was cased to the top of the Ordovician and then cored through the Ordovician and Cambrian sequence to the Precambrian basement. In Phase 2 of the GSCP, boreholes DGR-3 and DGR-4 were drilled and cored through to the Cambrian. In combination, boreholes DGR-1 through DGR-4 triangulate the footprint of the proposed repository. Results of other Phase 1 GSCP activities are described in Raven et al. (2007).

An important component of the GSCP is the acquisition of in-situ estimates of rock mass hydraulic conductivity (K), and, to a lesser extent, other hydrogeologic formation properties including formation pressure (P_f) and specific storage (S_s). The straddle-packer hydraulic test program described in this paper was designed to acquire representative formation hydraulic conductivities for Silurian to Ordovician age sediments within the approximately 650 m uncased lengths of the DGR-3 and DGR-4 boreholes.

2 BACKGROUND

Straddle-packer testing uses two or more inflatable packers to isolate a section of borehole (the test interval) for testing. Such testing is usually performed subsequent to completion of all drilling activities. Straddle-packer testing equipment has been commonly used to evaluate formation properties of interest to oil and gas production.

The testing approach has also proven to be the most appropriate method for in-situ evaluation of low-permeability media, either as caprocks or as possible host rocks for deep geologic repositories. Bredehoeft and Papadopulos (1980) describe application of the pulse-testing approach used and present analytical solutions for test analyses. Pickens et al. (1987) provide an overview of hydraulic testing in low-permeability media and detail numeric analysis approaches which compensate for non-ideal, yet typical, low-permeability testing conditions such as pre-test borehole pressure history. Roberts et al. (1999) describe the equipment and test analyses used underground at the Waste Isolation Pilot Plant (WIPP) site in New Mexico to characterize extremely low-permeability evaporite formations.

Typically, straddle-packer equipment is used for conducting two types of well tests: slug tests and pulse tests. Slug tests record the rise or fall of the water level within a tubing string connected to the test interval in response to a near-instantaneous injection or withdrawal of fluid. Pulse tests record the pressure response of a “shut-in”, or isolated, test interval to a near-instantaneous pressure change. Slug tests are appropriate for formations with hydraulic conductivity between 10^{-6} and 10^{-9} ms^{-1}. Pulse tests are most useful for permeabilities below 10^{-10} ms^{-1}. A third test type, drill-stem test, or DST, is essentially a slug test followed by a pulse test and is used for formations with permeabilities between 10^{-8} and 10^{-10} ms^{-1}. This paper will focus on pulse testing in the Ordovician sequence, where most of the tested formations have hydraulic conductivities < 10^{-12} ms^{-1}.

3 TEST EQUIPMENT DESIGN

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.

3.1 Design Goals

The response of a formation to pulse testing is a function of the formation properties, the pulse magnitude, and the well-bore boundary condition. For a pulse test this boundary condition is:

$$q_w = C_{tz} \; V_{tz} \; dP/dt \qquad [1]$$

where:

q_w	flow rate	(m^3s^{-1})
C_{tz}	test-zone compressibility	(Pa^{-1})
V_{tz}	test-zone volume	(m^3)
P	test-zone pressure	(Pa)
t	time	(s)

For a given formation, the time required to obtain sufficient response for analyses will be proportional to the C_{tz} V_{tz}, or wellbore storage, term. Minimizing this value was a fundamental goal of the equipment design process.

C_{tz} is a composite compressibility that includes contributions from the test equipment, the borehole fluid, and the geomechanical response of the borehole wall. (Note that the presence of free-phase gas in the test zone considerably complicates test analyses as C_{tz} becomes non-linear as a function of pressure. None of the tests described in this paper had responses indicative of gas in the test interval). V_{tz} includes the volume of fluid between the packers and within any tubing or equipment components connected to the test interval.

Equipment reliability is also of paramount importance. Malfunctions when equipment is downhole lead to expensive and non-productive time to trip the equipment out of the hole, replace the malfunctioning component, perform equipment quality assurance tests, and then return to the interval being tested.

Another important design consideration is to support remote access to test results while testing is underway. This allows for off-site supervision of testing and for continuous monitoring of the test response. Remote access also allows for near real-time preliminary test analyses. Test supervisors and analysts at remote locations can consult with on-site staff to modify the testing approach if required.

A final design goal is that data be as accurate as reasonably possible and potential sources of interference be minimized. For example, during pulse tests in very low-permeability formations, slight variations in packer pressures can cause perceptible changes in test-zone pressure that can interfere with the actual formation response. Similarly, very small equipment leaks, that would be imperceptible in more permeable formations, can significantly alter test response and lead to overestimates of actual permeability. Controlling these variables reduces uncertainty in final analysis results.

3.2 Downhole Equipment

Downhole equipment consists of packers, shut-in valve, pulse generator, transducer carrier, and assorted feed throughs and connecting components, as shown in Figure 1. Note that the test interval shown in the figure is very short for presentation purposes. The actual test interval is much longer, as discussed below.

C_{tz} can be minimized through use of extremely stiff packers and strong interconnecting components. Baski geotechnical “Fracker” packers were used in the test-tool. They allow inflation pressures of up to 20 MPa over ambient borehole fluid pressure. Most tool feed throughs and connections are custom-machined stainless steel components.

The shut-in valve separates the test interval from the tubing string. When the packers are fully inflated, closing the shut-in valve isolates the test interval. The valve selected for use is a hydraulically operated ball valve manufactured by Inflatable Packers International Pty Ltd. Unlike mechanical valves typically used in commercial straddle-packer testing equipment, the hydraulic valve is effectively zero-displacement, where the act of closing the valve does not affect test-zone pressure.

The piston pulse generator is a hydraulic piston mounted in a chamber connected to the test interval. In an isolated test interval (i.e. after packer inflation and closing the shut-in valve), extending the piston will create a near-instantaneous pressure pulse. As the volume of the piston and test zone is known, the size of pulse can be used to directly calculate C_{tz}, which is a critical value for test analyses. The piston can be used to create pulse withdrawals by extending the piston prior to shut-in, and subsequently retracting the piston after the shut-in valve is closed.

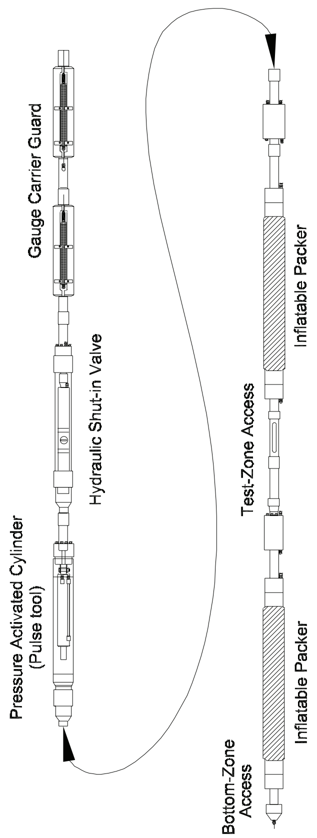

Figure 1. Schematic of down-hole equipment.

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. Fully digital Paroscientific submersible transducers with 0 to 14 MPa range and 0.01% accuracy (% full scale) are used. Four transducers can be mounted to monitor: test zone, bottom zone (below bottom packer), annulus (above top packer, outside tubing string) and tubing (above shut-in valve inside tubing string). Although the Paroscientific transducers will measure temperature, due to their location they do not measure the temperature in the test zone or below the bottom packer. HOBO temperature loggers are placed in the test zone and below the bottom packer to monitor temperatures in those intervals.

Selection of test-zone length is subject to conflicting constraints. Shorter test intervals reduce the wellbore storage term, but increase the number of tests that must be performed if continuous coverage is required. Average formation thickness provides an upper bound on test-zone length unless composite responses from several formations are acceptable. For the purposes of the testing in DGR-3 and DGR-4, an approximately 30-m test interval length was selected as a suitable compromise.

The downhole equipment is connected to surface with four stainless steel hydraulic lines (packer inflate/deflate, piston extend, piston retract, shut-in valve close) 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 the service rig at surface and the downhole tool.

3.3 Surface Equipment

With the exception of reels for the stainless steel hydraulic lines and the umbilical cable, all surface equipment is contained within a Mobile Integrated Aquifer Testing and Analysis (MIATA) laboratory. The temperature-controlled MIATA laboratory is enclosed in a customized trailer and is subdivided in two sections: a front section with office, computer, and DAS equipment; and a back section with workbench, intensifier pumps, and hydraulic line control panel.

All hydraulic lines are filled with non-toxic "plumbers" anti-freeze to allow for year-round operation. Pressure is provided by a pneumatically driven intensifier pump. Pressure regulation is accomplished with high-accuracy regulators controlling nitrogen charging on accumulators connected through the hydraulic control panel to the downhole equipment. Some pressure variation due to daily temperature fluctuations is inevitable; however the magnitude of the variation is minimized.

The DAS acquires data from the downhole probes and additional transducers measuring barometric pressure, and pressures on each hydraulic line. A user-friendly interface allows selection of sampling rates and specification of test identifiers. All data acquired are stored in a SQL data base. Data can be queried and viewed on-site, or can be accessed remotely over a secure web-based interface.

4 TEST METHODOLOGY

All field activities at the Bruce site are performed according to Test Plans, which are documents controlled by the Intera Engineering project specific quality plan. Test plans are developed and reviewed before work is started and describe testing procedures and associated records to be maintained. They are flexible and can be modified during testing to meet unforeseen eventualities.

The test plans include a description of Quality Assurance (QA) procedures to be performed before testing commences. These include leak testing on all tool components as the tool is assembled over the borehole, as well as one or more pulse tests conducted within the steel casing in the upper sections of the borehole.

The low-permeability Ordovician formations in borehole DGR-3 and DGR-4 were tested using pulse tests. In general, 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 test plan for pulse tests describes a multiple sequence test. 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 for a period of up to 24 hours. This stabilization period allows for any tool-dependent compliance effects, such as packer creep, to occur before testing is performed. Test-zone thermal effects are also minimized as any temperature disturbance caused by tool movement will equilibrate during this period.

After stabilization an initial pulse is generated. The direction of the pulse is based on assumed formation pressures. In DGR-3 and DGR-4, 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 Ordovician formations. Pulse-injection tests were performed on most low-permeability Silurian intervals and several of the deepest Ordovician intervals. Slug tests were performed on several of the more permeable Silurian formations.

In most Ordovician intervals, two pulse withdrawal tests were conducted. At the end of the first pulse withdrawal, fluid levels in the tubing string were adjusted to approximately equal the pressure measured in the test zone. The shut-in valve was opened, the piston extended, and the shut-in valve closed. The piston was then retracted, causing the second pulse withdrawal.

Figure 2 shows the test zone and bottom zone test response for test DGR3_671.50-702.24, conducted in the Cobourg Formation and spanning the proposed repository horizon.

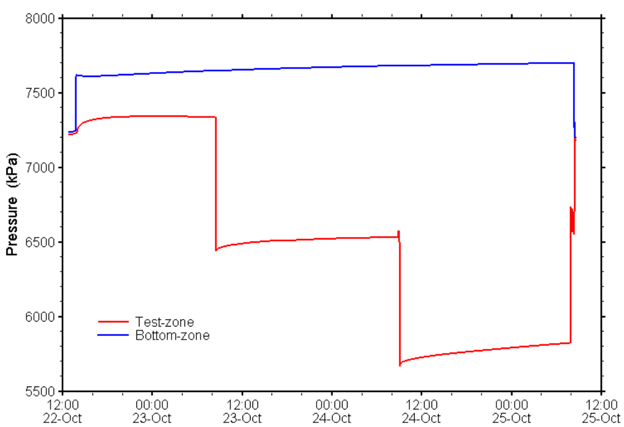

Figure 2. DGR3_671.50-702.24 test interval and bottom zone response.

Each pulse sequence was approximately one day in duration, with a total interval testing time of three days (one day stabilization, followed by two test sequences at one day each).

5 TEST ANALYSES

Pressure data collected during the hydraulic tests were analyzed using the nSIGHTS (NWMP, 2006) (n-dimensional Statistical Inverse Graphical Hydraulic Test Simulator) code to estimate hydraulic conductivity and formation pressures of the tested intervals. The nSIGHTS code has been used in nuclear repository characterization programs around the globe, including Canada (OPG), the USA (WIPP), Sweden (SKB), France (Andra), and Japan (JNP). nSIGHTS 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.

The first step in the analysis process is conceptual model identification, based on the observed pressure-response characteristics and knowledge of the hydrogeologic system. Initial values are then determined for both fitting and non-fitting parameters in the model. Fitting parameters are the desired analysis results and include hydraulic conductivity, static formation pressure, specific storage and, if required by the conceptual model, skin parameters. For pulse tests, C_{tz} is a non-fitting parameter calculated from pulse magnitudes and test-zone volume. In the next step, non-linear regression, or optimization, is used to refine the initial fitting-parameter estimates, resulting in baseline fitting-parameter values that produce an acceptable fit to the measured test response.

The baseline-fit parameter values are then randomly perturbed a specified number of times and the problem is re-optimized for each perturbation to investigate the uniqueness of the solution. This process shows the ranges over which the fitting-parameter values can vary while still producing an acceptable fit to the field data, i.e., the perturbation process quantifies the uncertainty.

Figure 3 shows the testing sequence performed in interval DGR3_671.50-702.24 along with the best-fit nSIGHTS simulations. This testing sequence was preceded by approximately three months of variable pressure history, shown in Figure 4. This history describes the pressures in the test interval from the time that the interval was first intercepted by drilling. The full pressure history is included in the nSIGHTS simulations and is critical for accurate parameter estimation in low-conductivity formations. The range of perturbation-derived K and P_f values corresponding to the best-fit simulations in Figure 3 are shown in Figure 5.

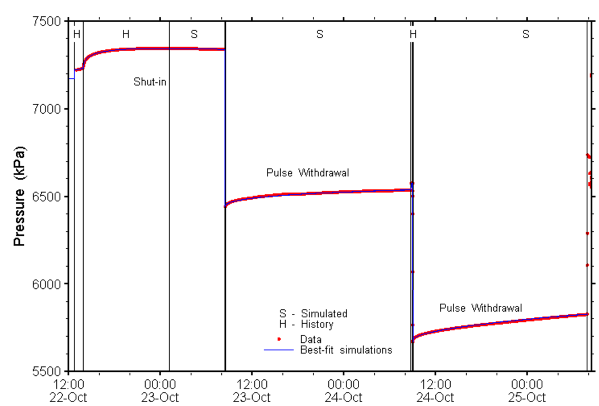

Figure 3. Annotated DGR3_671.50-702.24 testing sequence showing best fit simulation and parameter estimates.

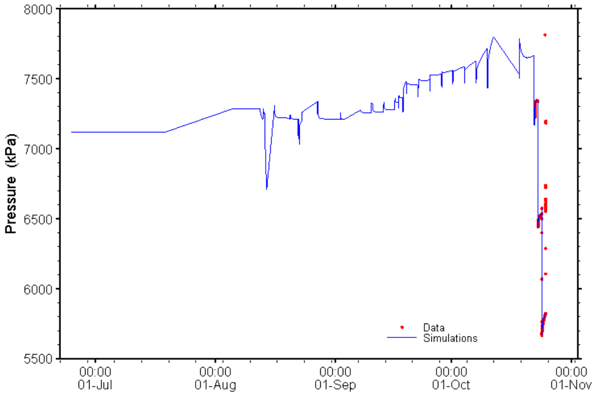

Figure 4. DGR3_671.50-702.24 testing sequence showing the three-month pressure history that preceded testing.

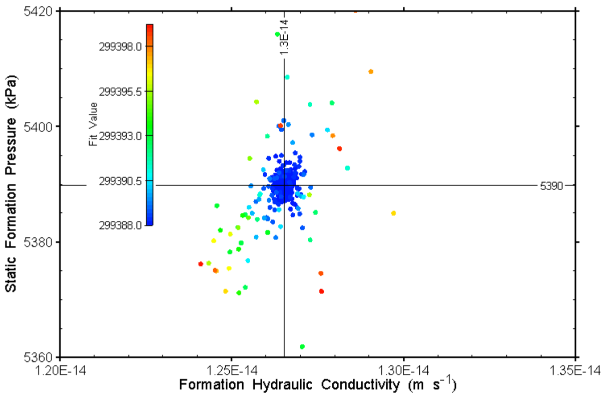

Figure 5. XY-scatter plot showing estimates of formation hydraulic conductivity and static formation pressure derived from the DGR3_671.50-702.24 perturbation analysis.

The C_{tz} estimate for test DGR3_671.50-702.24 calculated from the pulse withdrawals was 3.6 x 10^{-10} Pa^{-1}. This is approximately the value for water, indicating that packer and formation compressibility were minimal.

There is evidence from other site characterization activities that free-phase gas may exist within the rock mass. This will affect the formation response to hydraulic testing. nSIGHTS is a single-phase (water or gas) code. Scoping simulations are being performed using TOUGH2 (Pruess et al. 1999) to investigate the impact of multi-phase flow on response to hydraulic testing.

6 PRELIMINARY RESULTS

Testing was performed in borehole DGR-3 from 7 Sept 08 through 14 Nov 08. A total of 23 hydraulic tests were conducted. An equipment failure occurred on 11 Oct 08 when communication with the transducers was lost. Testing resumed six days later, after the umbilical cable was replaced with a spare. DGR-4 testing started on 25 Nov 08 and continued through 22 Feb 09 with no equipment failures. Twenty-four tests were conducted in DGR-4.

Figure 6 shows estimates of formation hydraulic conductivity and pressure in borehole DGR-3 based on preliminary test analyses conducted during testing. These results are generally the output from a single regression and do not include perturbation analyses as described in Section 5. These preliminary estimates may change slightly during final analyses but are expected to be representative.

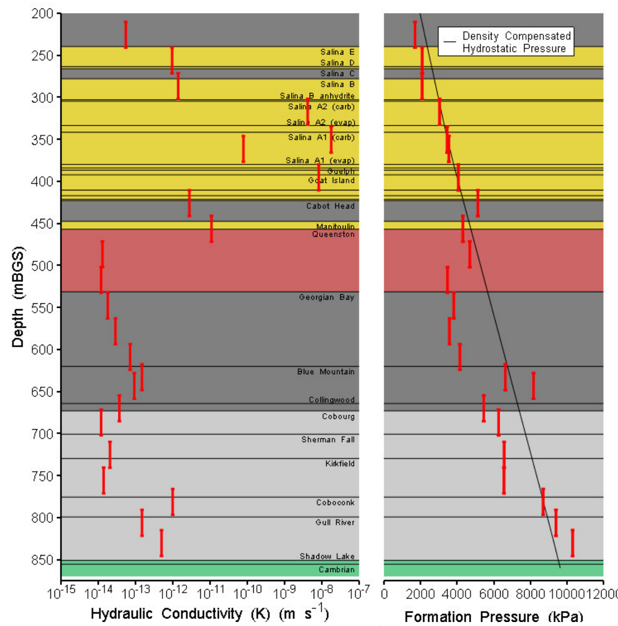

Figure 6. Preliminary estimates of hydraulic conductivity and formation pressure in borehole DGR-3.

The Silurian intervals (above the Queenston shale) are generally very low-permeability in the shales and dolostones. The three higher permeability tests (i.e. greater than 10^{-9} ms^{-1}) are associated with two relatively thin (less than 5 m) intervals at the top of the Salina A1 carbonate and the Guelph Formation. Formation pressures within the Silurian are near hydrostatic except for underpressures in the upper shales and overpressures in the lower carbonates below the Guelph.

Permeabilities in the Ordovician sequence are extremely low, with the lowest hydraulic conductivity (1.3 x 10^{-14} ms^{-1}) in the Cobourg Formation. Underpressures are also found over most of the sequence. The genesis of these underpressures is currently unknown, although presence of a separate gas phase in the formation, and/or erosional unloading are possibilities. The overpressures in the Gull River Formation are likely due to a hydraulic response to the more permeable Cambrian, which was determined to be significantly overpressured at the completion of DGR-3 drilling.

Preliminary results for DGR-4 are presented in Figure 7. DGR-4 results are largely consistent with DGR-3, although Ordovician underpressures in DGR-4 were of greater magnitude with results for one test showing liquid formation pressures near zero. Permeabilities in DGR-4 are consistent with DGR-3, with most Ordovician formations having hydraulic conductivities between 10^{-13} and 10^{-14} ms^{-1}.

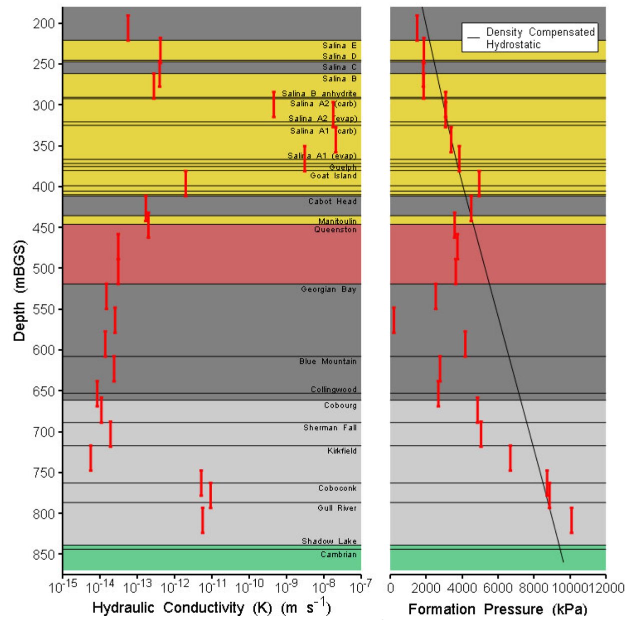

Figure 7. Preliminary estimates of hydraulic conductivity and formation pressure in borehole DGR-4.

7 FUTURE WORK

Phase 2 testing will continue in 2009 with the drilling and coring of two inclined boreholes; DGR-5 and DGR-6. Straddle-packer testing will be conducted on selected intervals, rather than continuously over the entire borehole length. The straddle interval will likely be reduced substantially to characterize smaller features and to avoid problems with equipment bending.

8 CONCLUSIONS

A state-of-the-art test tool and trailer-based support laboratory have been designed and built to carry out straddle-packer testing at the Bruce site.

A total of 47 hydraulic tests were conducted over a six-month period in boreholes DGR-3 and DGR-4. These tests provide continuous coverage of the Silurian and Ordovician sediments at the Bruce site. Comparison of results between boreholes shows consistent hydraulic conductivities on a formation basis.

Preliminary analysis results of the DGR-3 and DGR-4 testing show hydraulic conductivities of 10^{-14}ms^{-1} to 10^{-13} ms^{-1} in the Ordovician units above and surrounding the proposed repository horizon. These extremely low permeabilities indicate a diffusion-dominated transport regime. This will significantly contribute toward the safe long-term containment and isolation of the Low and Intermediate Level Radioactive Waste in the proposed Deep Geologic Repository.

ACKNOWLEDGEMENTS

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REFERENCES

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

Intera Engineering Ltd. 2006. *Geoscientific Site Characterization Plan, OPG's Deep Geologic Repository for Low & Intermediate Level Waste*. OPG Report 00216-REP-03902-00002-R00, April.

Intera Engineering Ltd. 2008. *Phase 2 Geoscientific Site Characterization Plan, OPG's Deep Geologic Repository for Low and Intermediate Level Waste, Report,* OPG Report # 00216-REP-03902-00006-R00, April.

Nuclear Waste Management Program. 2006. *nSIGHTS 2.40 User Manual Version 2.1*. ERMS #530161. Carlsbad, NM: Sandia National Laboratories.

Pickens, J.F., G.E. Grisak, J.D. Avis, D.W. Belanger, and M. Thury. 1987. Analysis and Interpretation of Borehole Hydraulic Tests in Deep Boreholes: Principles, Model Development and Applications. *Water Resour Res*, 23(7):1341-1375

Pruess, K., C. Oldenburg and G. Moridis. 1999. *TOUGH2 User's Guide*, Version 2.0. LBNL-43134. Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California.

Raven, K., S. Sterling, J. Avis, R. Jackson and M. Jensen, 2007. Geoscientific Site Characterization Plan for the Deep Geologic Repository at the Bruce site, Kincardine, Ontario. *Proc. 60th Canadian Geotechnical Conf. & 8th Joint CGS/IAH-CNC Groundwater Conf., Ottawa*, pp 628-635.

Roberts, R.M, R.L. Beauheim, and P.S. Domski. 1999. *Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Final Report.* SAND98-2537. Albuquerque, NM: Sandia National Laboratories.