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DEEP BOREHOLE TESTING TECHNIQUES DEVELOPED FOR CANADA'S NUCLEAR FUEL WASTE MANAGEMENT PROGRAM

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ABSTRACT

Atomic Energy of Canada Limited's nuclear fuel waste management program is presently centred around the concept of deep burial of immobilized fuel waste within igneous plutons of the Archaean Canadian Shield. Contaminant transport within this host medium would be by movement through rock fractures. Consequently, as part of the overall concept assessment phase, hydrogeological research has been initiated to assess potential pathways for contaminant leaks to the biosphere. Determination of accurate rock mass and fracture hydraulic conductivities and travel times are essential to the deep burial concept.

Five continuously cored, inclined boreholes have been drilled to equivalent vertical depths up to 1100 m into the Eye-Dashwa Lakes pluton of Northern Ontario. This granitic body is a massive, medium to coarse grained hornblende - biotite granite which is intrusive into a series of tonalitic gneisses. Detailed core logging and surface fracture mapping have provided fracture geometry data as vital input to the on-going hydrogeological research.

Slim-hole, single - and double-packer assemblies including downhole transducers and thermistors have been developed to measure transient and steady state pressures and temperatures. Downhole measurements are multiplexed to surface recording equipment via a single conductor cable. Pressure and temperature responses can be observed as frequently as every four seconds. Essential test data are recorded on magnetic tape. The on-site, surface data acquisition system has the capability of plotting the pressure-temperature data as it is recorded, thus allowing immediate inspection and evaluation of test data.

Preliminary analysis of hydraulic data indicate that at least three discrete flow regimes may exist within the pluton. Hydraulic conductivity values show a general decrease with depth, although

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zones of relatively high hydraulic conductivity do occur: values range from 10^{-6} m/s near the surface to about 10^{-13} m/s at 1000 m vertical depth, when porous medium analysis is used.

INTRODUCTION

Atomic Energy of Canada Limited's nuclear fuel waste management program is presently centred around the concept of deep burial of immobilized fuel waste within igneous plutons of the Archaean Canadian Shield. Potential contaminant transport within this host medium is by movement through rock fractures. Consequently, as part of the overall concept assessment phase, hydrogeological research has been initiated to assess potential pathways for contaminant leaks to the biosphere. Determination of accurate rock mass and fracture hydraulic conductivities and travel times are essential to the deep burial concept. This paper describes the equipment and sampling techniques used in one part of the current hydrogeological research program.

The study area is located in northwestern Ontario approximately half way between the City of Thunder Bay and the Town of Fort Frances, some 17 km north of the Town of Atikokan, (Fig. 1). The site is situated on the Eye-Dashwa Lakes pluton, which is a massive, medium to coarse grained hornblende-biotite granite. This granitic rock mass is intrusive into a surrounding series of tonalitic gneisses (ref. 1). Detailed borehole core logging and surface fracture mapping have provided necessary input to the ongoing hydrogeological research.

Fig. 1
Test site location

Basically three different equipment assemblies have been developed for the hydrogeological program. A single-packer unit used for through-the-bit testing during drilling operations; a double-packer unit developed for transient testing of selected fracture sets in open boreholes; and finally, geochemical equipment required for ground water sampling from packed-off fracture zones. Highlights of the results obtained from these equipment assemblies are summarized in a later section of this paper.

SAMPLING EQUIPMENT

Single-packer assembly

A single-packer assembly comprising an integrated surface and downhole instrumentation system was designed specifically to allow through-the-bit pressure and temperature monitoring during drilling. This equipment was designed and fabricated by Science Applications Incorporated, New Mexico, U.S.A. to operate within inclined boreholes of 76 mm diameter.

The single fluid-inflatable packer, (Figure 2), is lowered within the drill string to exit beneath the coring bit into the open borehole. Inflation pressure is transmitted to the packer through a high-strength tubing contained on a heavy duty cable reel assembly. The cable reel assembly facilitates control for raising and lowering the packer assembly in the borehole. The downhole electronics assembly contains pressure transducers and thermistors located both above and below the packer. These sensors provide data before or after packer inflation related to the in-situ conditions both above and below the packer and therefore enable immediate monitoring of any changes occurring after inflation.

The complete electronics package includes circuitry that provides regulated bias to the temperature and pressure transducers. A multiplexer digitizes and transmits these data on a single conductor cable to surface recording instrumentation. The system is designed to operate over a temperature range of -5°C to 50°C and will operate at depths in excess of 1,000 m to pressures of 34,500 kPa.

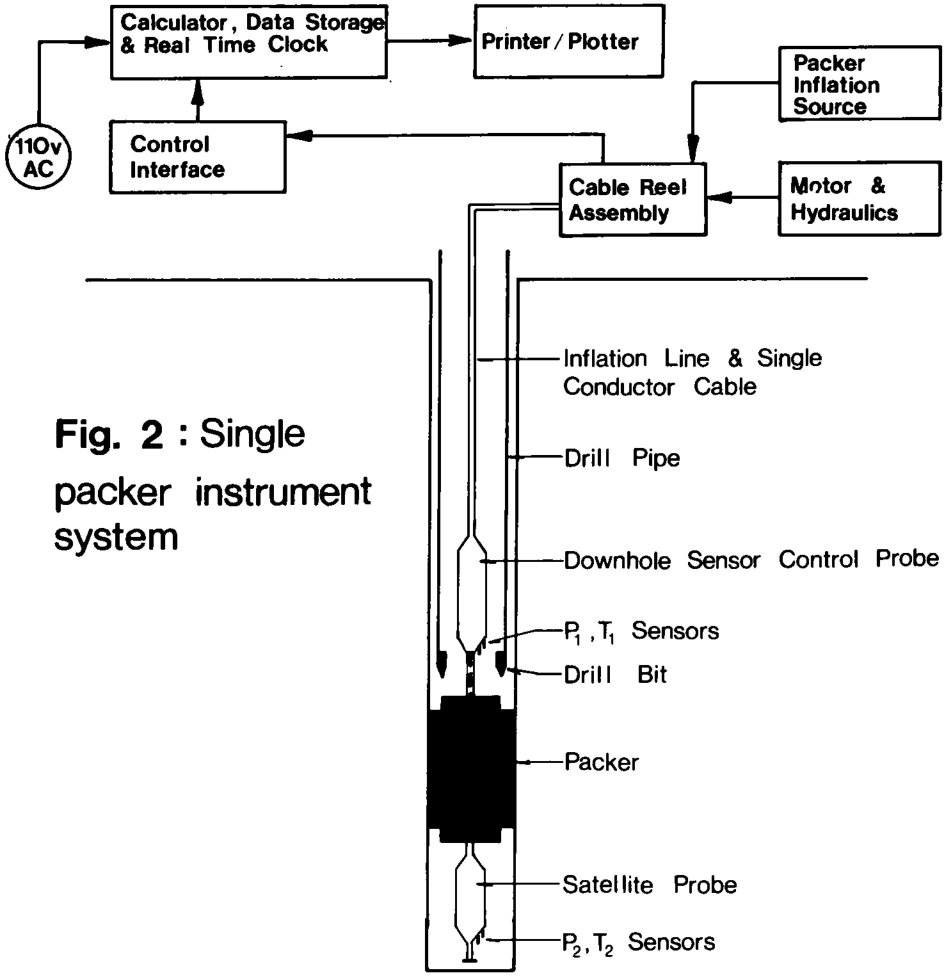

Fig. 2 : Single packer instrument system

The surface instrumentation includes three components: a control unit, a calculator and a printer/plotter. The control unit supplies the power to the downhole electronics, accepts multiplexed digital data from the downhole unit, and demultiplexes these data and sends the information to the calculator. The calculator processess four channels of data, two temperature and two pressure signals. The processed data may be observed on the calculator's LED display, printed out, or stored on an on-board cassette tape. In addition, these parameters may be plotted and/or printed by the printer/plotter. Data from all channels can be printed and/or stored on tape as frequently as every two and four seconds respectively. The calculator includes versatile program software that processess the information and controls the printout and display functions.

Double-packer assembly

The double-packer equipment was designed and fabricated by Lynes United Services Limited, Texas, U.S.A., to allow hydrogeological testing and geochemical sampling from selected intervals in an open borehole. This equipment can operate to depths in excess of 2,000 m and similar instrumentation in the oil industry has been successfully used to depths of 8,000 m under much higher temperature and pressure conditions. The double-packer system consists of a straddle packer assembly interfaced with a downhole electronics/ sensor carrier which transmits data through a single conductor cable to the surface monitoring equipment, (Fig. 3). Pressure data for the zones above and below as well as in the straddle interval are provided by porting the three transducers to these zones.

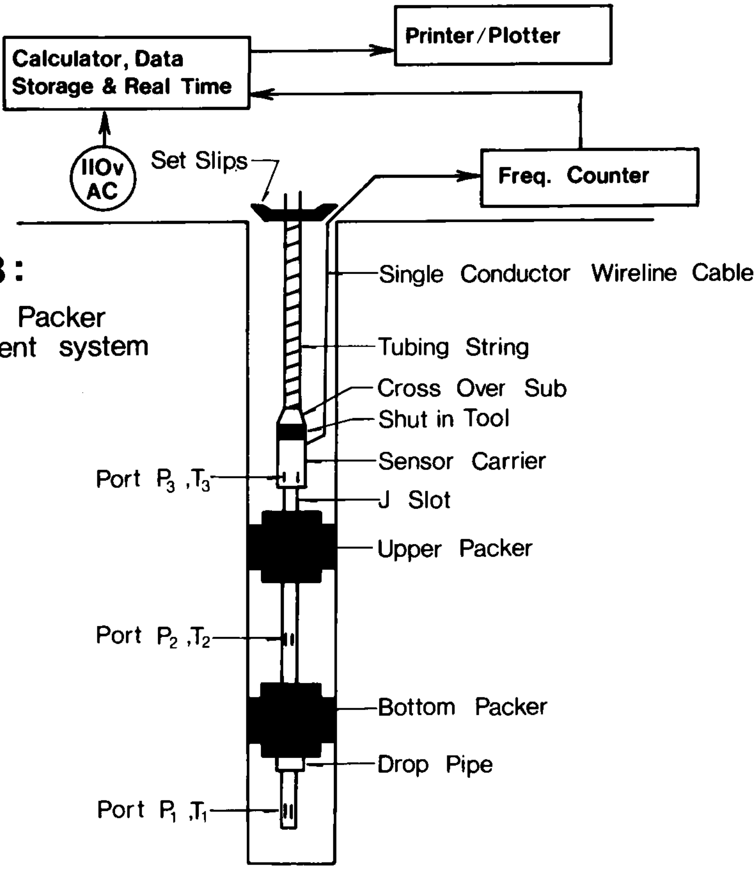

Fig. 3: Double Packer Instrument system

The double-packer assembly is run into the borehole on a conventional steel tubing string. At the top of the double-packer assembly is a shut-in tool which allows isolating the straddled interval from the open tubing string above the zone of interest. This isolation capability is critical for performing static as well as transient tests in the borehole.

The pressure sensors are quartz-type transducers which can provide a much higher degree of resolution and accuracy than bourdon-type diaphragm gauges more commonly used in the past for deep borehole testing. The pressure and temperature data are transmitted from the downhole sensor probe over a single conductor wireline to an on-surface interface unit. These measurements are converted from frequency signals to pressure and temperature readings that are printed, plotted and stored on magnetic tape. The data acquisition rate, a six channel output every 24 s, is relatively slow in comparison to analog output. However, at this stage of the testing program increased pressure resolution is considered more important than more rapid data acquisition techniques.

Software for the on-surface equipment allows printout of the data stored on magnetic tape as well as on-site plotting for type-curve and best fit straight line analysis methods. This plotting facility can greatly reduce the time needed for evaluation but more importantly, provides an immediate assessment of whether or not interval information is adequate for analysis.

Geochemical equipment

Ground water samples were collected from selected test intervals where the fracture hydraulic conductivity was high enough to yield sufficient water for sampling by the geochemical equipment. Ground water samples were removed from the boreholes by suction-lift pumping, swabbing, air-lift pumping and with a nitrogen driven piston type sampling pump. Most test intervals below 200 m depth yielded insufficient ground water for geochemical sampling. Except for the air-lift pumping technique all other samples were brought to the surface through air-free nylon tubing. The samples passed through a flow-through cell for measurement of pH, Eh and conductivity. Other field analyses included chloride ion, alkalinity and hardness. Further samples were collected and appropriately preserved for more detailed laboratory analysis.

Production injection packers (PIPs) were used to isolate selected intervals in boreholes deeper than 200 m. At these depths low hydraulic conductivities precluded collection of ground water samples through the double-packer assembly within short time frames. These packers, therefore, were left in place for approximately eight months and the fracture systems were allowed to respond. Sampling of ground water through the PIPs can be done without deflating the packer element. This technique proved to be useful and cost effective method of obtaining 'true' formation water.

PRELIMINARY RESULTS

Assessment of transient hydraulic data has shown that fractured medium testing can yield some results that may be interpreted by type-curve matching as equivalent porous medium. However, in other instances pressure responses may only be attributable to fracture flow. Porous medium solutions in many cases violate the inherent assumptions for fracture flow analyses. More research is needed to refine testing and analysis methods in fractured medium. Scale effects obviously affect the flow system. At the test site large concentrations of fractures were mapped both on surface and in logged subsurface cores. Many of the hydraulic test data match equivalent porous medium analyses which may reflect that the conditions tested are at a larger scale than individual single fractures. On a smaller, fracture by fracture basis, more atypical results may be demonstrated. Future testing will evaluate this approach.

Hydraulic heads were measured using both the single and double-packer assemblies. The hydraulic head distribution for one borehole, ATK-1, indicate downward gradients to about 550 m and upward gradients in the zones examined at vertical depths greater than 990 m, (Fig. 4).

Hydraulic conductivity values were calculated from transient pressure testing data provided by the double-packer assembly. Different testing techniques were used on the same test interval for comparison purposes. The following tests were used: slug injection/withdrawal, pulse withdrawal, drill stem tests, airlift pumping/recovery and constant rate injection tests. Generally the hydraulic conductivities determined from these tests were comparable within one order of magnitude and as expected decreased with depth. Hydraulic conductivity varies with depth and values range from 10^{-6} m/s near the surface to 10^{-13} m/s at 1000 m (Fig. 4).

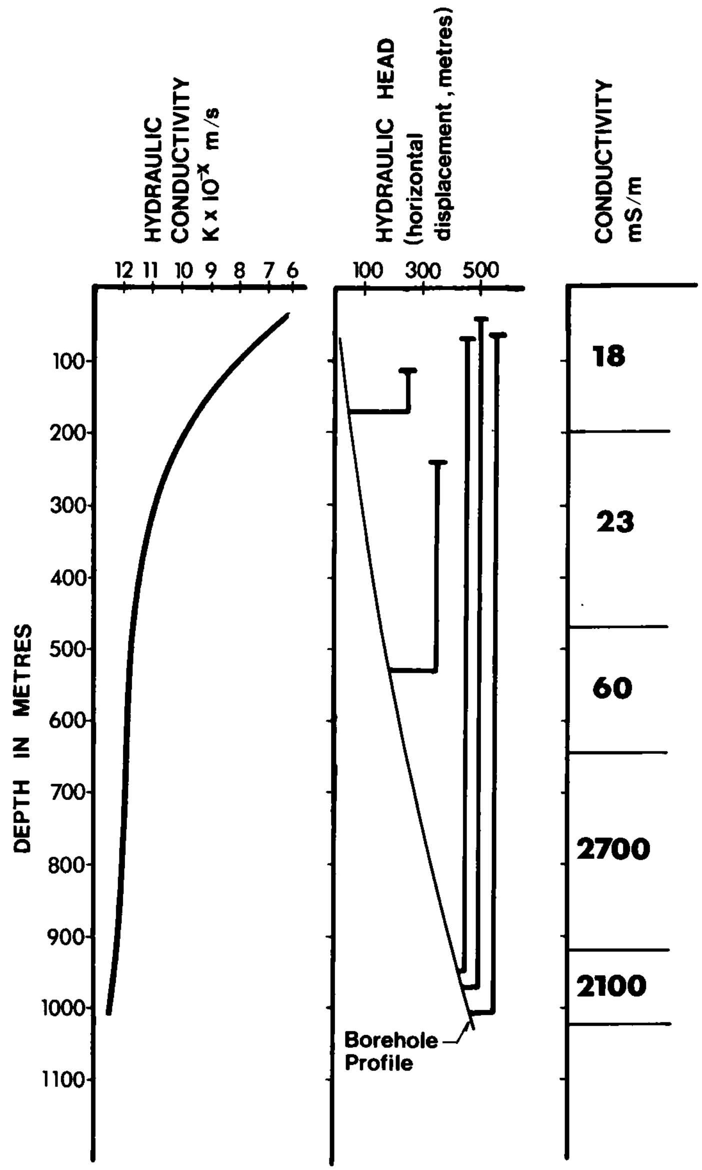

Fig. 4 : Hydrogeological summary of borehole ATK-I

The concept of matching slug and pulse test data to porous medium type curves is established (refs. 2-4). Most curves, however are based on assumptions that are invalid for single or multiple planar type features. Data match the type curves only if the medium responds in a porous medium manner. Fractured medium can respond like porous medium when the magnitude of fracturing and interconnection approximates porosities typical of porous medium. Hydraulic test data were also interpreted using equations developed for equivalent single fracture and equivalent rock mass hydraulic conductivities (refs. 5-7). Generally good comparison was noted between equivalent single fracture, equivalent rock mass and porous medium hydraulic conductivities. On the other hand hydraulic conductivities in tighter zones showed equivalent rock mass values one to two orders of magnitude greater than porous medium values.

The TERZAGI code, a modified version of the TRUST computer program (ref. 8), was used to analyse test data, where the corresponding orientated fracture information was available. The assumptions made for operating this code were: radial fracture symmetry, one single horizontal fracture intersecting the borehole, and a no-flow external fracture boundary. Then by simply varying the input fracture aperture width a series of type curves were generated for matching the test data. Results of the TERZAGI simulation predicted single fracture aperture widths that compare favourably with the apperture widths predicted by equivalent single fracture analysis technique.

Geochemistry

Results of geochemical analyses of water samples collected from different depths in the pluton are shown in Table 1. Ground water composition changes at a depth of approximately 700 m from a $Ca-HCO_3-SO_4$ water to a Na-Ca-Cl brine. Electrical conductivities above 700 m ranged from 18 mS/m to 60 mS/m and below 700 m from 2100 mS/m to 2700 mS/m, (Fig. 4). Currently work is being undertaken to define more accurately the boundaries between the fresh ground water and the brines at depth. In addition samples are being collected for isotopic dating of the ground water.

Ground water temperature measurements were made in each borehole using the double-packer assembly and also by running temperature logs. These two sets of results gave thermal gradients of $1.1^{o}C$ and $0.7^{o}C$ per 100 m of depth respectively. These gradients compare favourably with results obtained by others in similar geological settings elsewhere in Canada (refs. 9-10).

TABLE 1
CHEMICAL ANALYSES ATK-1*

DEPTH + (m)	Ca	Mg	Na	K	Sr	Fe	Mn	SO_4	Cl	Br	F	HCO_3	TOC	Electrical Conductivity (mS/m)
171-187	22.3	3.6	14.4	2.1	-	0.21	0.21	17.4	22.0	-	1.3	59.8	-	14.5
0-212	32.3	5.7	7.4	2.5	0.35	33.7	1.1	5.0	8.0	<0.5	0.25	134	8.9	18
212-504	27.2	3.5	8.0	2.2	0.36	28.6	1.4	13.5	26.9	<0.5	<0.1	65.5	9.1	23
504-746	106	1.8	35.3	2.2	1.7	7.8	0.85	149	151	1.0	0.92	14.5	15.8	60
746-1003	5525	1.9	1200	9.8	103	19.0	1.8	74.1	10,000	<0.5	<0.1	<7.0	13.4	2700
1003-1152	3700	1.8	747	7.6	82.0	4.8	1.2	410	7995	74.5	<0.1	<7.0	-	2100

* Results are average of duplicate analyses, and are reported as mg/L unless otherwise stated.

\+ 171-187 m sample was collected during double-packer testing, other samples were collected through production injection packers.

CONCLUSIONS

1. All equipment assemblies used on this project performed according to specifications. Several modifications were made in the field to more efficiently expedite the operating procedures.
2. Hydraulic test data indicate a general decrease in hydraulic conductivity with depth, although zones of relatively high hydraulic conductivity occur at irregular intervals which are likely attributable to discrete fracture flow. Limited hydraulic head measurements show a complex system of unconfined and leaky fractures at shallow depths, below these, confined responses have been recorded.
3. Future testing and analyses of hydraulic test data will examine more fully an interconnected fracture flow approach both in collecting and interpreting these data.
4. Electrical conductivity increases with depth from 18 mS/m in the upper 200 m to 2700 mS/m at 1000 m. The chemical composition of the ground water changed from a $Ca\text{-}HCO_3\text{-}SO_4$ enriched water to a Na-Ca-Cl brine at approximately 700 m depth. Temperature transient measurements indicate a thermal gradient of 1^oC per 100 m .

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