MONITORING AND SAMPLING OF GROUNDWATER BENEATH DEEP PERMAFROST

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ABSTRACT
Monitoring and sampling of groundwater beneath permafrost is problematic. A new method using the "Thermos bottle" concept was developed to enable sampling, hydraulic testing, and measuring water levels beneath more than 300 m of permafrost. This sub-permafrost well included HQ drill rods as casing, a footvalve, heat trace cable, and a pressurized wellhead. The HQ casing was allowed to freeze in place, eliminating the need for grouting. The footvalve assembly kept water from entering and freezing within the HQ casing during its placement. Inside the casing, nominal 25-mm diameter steel pipe (the so-called inner pipe) was then connected to the footvalve, allowing groundwater to rise for sampling and measuring of water levels. To prevent water in the inner pipe from freezing during sampling, the pipe was heated with heat cable. Between sampling/measuring events, compressed nitrogen pushed water out of the inner pipe. For subsequent sampling/measuring, the heat cable would be re-activated; and the pressure released, allowing water to rise within the inner pipe. Water samples were collected by airlift pumping, and hydraulic conductivity was estimated from airlift recovery data.

RÉSUMÉ
La surveillance et l'échantillonnage de nappes phréatiques au-dessous du permafrost est problématique. Une nouvelle méthode utilisant le concept de la "bouteille thermos" a été développée pour permettre l'échantillonnage, les essais hydrauliques et la mesure des niveaux d'eau sous plus de 300 m de permafrost. Ce puits sous le permafrost comprenait des aciers de foreuse au diamant HQ comme cuvelage, une valve à pied et une source d'eau pressurisée. Le cuvelage HQ a été laissé se geler en place, éliminant ainsi le besoin de cimenter. La valve à pied a empêché l'eau de pénétrer et de geler à l'intérieur du cuvelage HQ pendant son positionnement. A l'intérieur du cuvelage, une conduite en acier d'un diamètre nominal de 25 mm (la soi-disant conduite intérieure) a été raccordée à la valve à pied, permettant à la nappe phréatique de monter pour l'échantillonnement et la mesure des niveaux d'eau. Pour empêcher que l'eau qui se trouve dans la conduite intérieure ne gèle pendant l'échantillonnage, cette conduite a été réchauffée avec un câble chauffant. Entre les échantillonnages et les mesures successives, de l'azote comprimé a été utilisé pour souffler l'eau hors de la conduite intérieure. Pour les échantillonnages et les mesures subséquents, le câble chauffant a été réactivé et la pression relâchée, permettant à l'eau de remonter à l'intérieur de la conduite. Des échantillons d'eau ont ainsi pu être prélevés, et la conductivité hydraulique a pu être estimée.

1. INTRODUCTION

Feasibility studies and environmental impact assessments for proposed mines in the Canadian North usually include predicting the quantity and quality of mine water discharge (from either dewatering wells or in-mine sumps) during mining, the chemistry of any pit lakes that might form upon cessation of mining, and long-term, post-mining groundwater conditions in the vicinity of the mine. These predictions are usually done with numerical groundwater flow and transport models. Such models require as input data on the hydraulic conductivity of various hydrogeologic units and the variation in the chemistry of the water they contain with depth. In areas in which thick permafrost underlies much or all of the dry land, obtaining such data can be quite problematic.

Sampling and conducting hydraulic testing beneath permafrost presents several unique technical challenges (Dept. of the Army, 1994). Diamond core drilling through the permafrost often requires use of a brine drilling fluid to prevent the drill rods from freezing in place during any non-drilling periods (e.g., while conducting hydraulic tests, during breakdowns, etc.). The saline drilling fluid usually invades the formation -- especially in the more permeable, water-bearing intervals -- and this requires a considerable amount of time to purge the well and adjacent formation of the "exotic" fluids before representative groundwater samples can be obtained. Many hydrogeologic studies have documented increases in salinity with depth; but usually there is a lot of scatter in the data, suggesting truly representative samples were not always obtained.

In addition to the groundwater sampling conducted during drilling, it is desirable to monitor the water chemistry over time. Typical monitoring wells used in warmer climates will obviously not work because the water inside the casing will freeze within the permafrost interval. As will be described below, several methods of installing monitoring wells have been used with limited success (D.E. Lawson, Cold Regions Research and Engineering Laboratory, 2006, personal communication; Lawson et al., 1998).

To both overcome the problem of long purge times which consumes expensive rig time and to facilitate sampling over time, Hydrologic Consultants Inc. (HCI) has designed and installed a new type of sub-permafrost monitoring well that can be sampled over time with minor power, equipment, and manpower requirements.

2. BACKGROUND

Descriptions of hydrogeologic investigations in arctic regions are contained in several documents by the Canadian Geological Survey, the National Snow and Ice Data Center (NSIDC), and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL).

CRREL has installed groundwater monitoring wells through 30 m of permafrost using compressed air introduced at the wellhead to keep the water level inside PVC casing below the base of the permafrost (Lawson et al., 1998). Most of these wells lost their pressure over time and froze. Although some of the wells were initially recovered by melting the ice inside the casing with a hot water pressure washer, most of the casings cracked from the freezing process and could not be re-pressurized for long-term use.

The site for the sub-permafrost monitoring well described in this paper was on land approximately 400 m from the shore of a lake and about 15 m above the elevation of the lake surface. Based on available data from the National Snow and Ice Data Center (NSIDC, 2003), Heginbottom and Dubreuil (1993), and the Diavik and Ekati diamond mines to the northwest, the thickness of the permafrost at this location was predicted to be about 200 m. To confirm this thickness prior to drilling the corehole for the sub-permafrost well, a string of 10 thermistors was installed at 25-m intervals in a 250 m deep corehole less than 10 m away. Because of limited availability of the drilling equipment, only two weeks of thermistor data could be obtained before the well had to be installed. However, the thermistor data, shown in Figure 1, clearly indicated that the permafrost was significantly thicker than 250 m. Beyond the depth where there is a gradient reversal due to near-surface seasonal effects, the temperatures below about 100 m to the last thermistor at 250 m showed an almost linear gradient. Extrapolating the temperatures to the freezing line (which was corrected for salinity and pressure), the bottom of the permafrost was defined to be in the range of 300 to 320 m below ground surface.

3. DESIGN OF SUB-PERMAFROST WELL

HQ drill rods were used as the well casing to utilise both the drilling equipment and the materials that were already on site for the concurrent exploration drilling program. A footvalve assembly which screws onto the bottom end of the HQ drill rods prevents water from entering the casing during installation. Once the casing is installed in the borehole, it is allowed to freeze in place, requiring no grouting. Inside the casing, a nominal 1-inch (25-mm) ID schedule 80 steel pipe (inner is screwed into the footvalve assembly, allowing groundwater to rise for sampling, testing, and monitoring (Figure 2). This dual-tube system acts like a Thermos bottle. The inner sample pipe, which is filled with water during sampling and testing, is insulated from the sub-freezing temperatures outside the casing by the air space. To provide additional protection against freezing, mineral-insulated copper heat trace cable is attached to the inner pipe. The annulus between the inner pipe and the casing is designed to remain empty (dry) and can be pressurized if required. During the periods of time between sampling events, the inner pipe and the annulus are pressurized with compressed nitrogen to maintain the water level in the inner pipe at a depth below the base of the permafrost. Thermocouple sensors are attached at 2 locations along the inner pipe to monitor the temperature of the inner pipe, indicating to the operator when the pressure can be released and groundwater can be allowed to rise in the inner pipe.

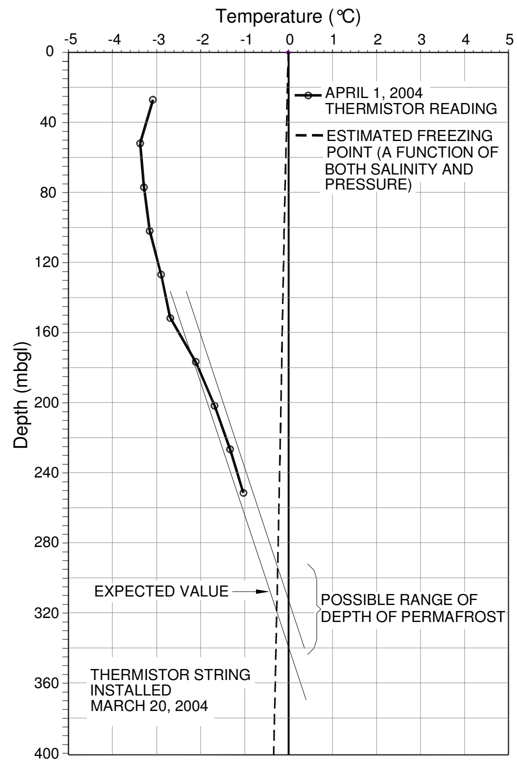

Figure 1. Thermistor data indicating depth of permafrost

The footvalve, shown in detail in Figure 3, has threads that screw onto the bottom of the HQ drill rods. It includes one large and four small brass, cartridge-style check valves that fit into machined passageways; and the valves are sealed against the passageways with rubber o-rings. All of the check valves are oriented so as to prevent water under pressure from the formation entering the footvalve. The large check valve, in the center of the footvalve assembly, is opened by screwing an adaptor attached to inner pipe into it. This check valve subsequently remains open. The smaller check valves can be opened by internal gas pressure to purge any water in the annulus between the inner pipe and the casing. These small check valves remain closed unless the wellhead is pressurized beyond hydrostatic pressure with nitrogen, at which point water (or nitrogen) is forced out through them.

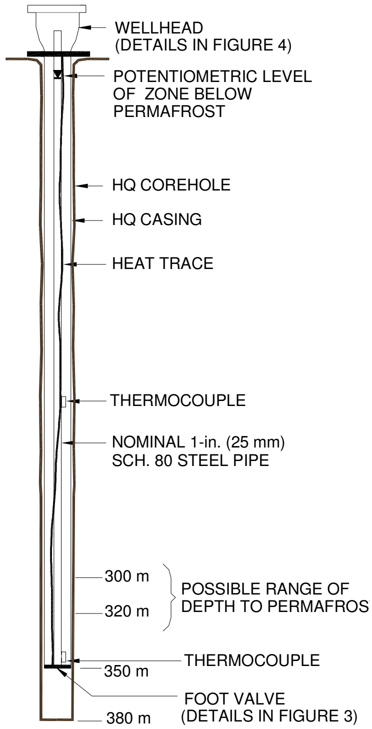

Figure 2. Schematic diagram of sub-permafrost monitoring well

The wellhead is of a two-piece, flanged design. The bottom half screws onto the top of the HQ rods, and the top half is bolted onto the bottom half. The purpose of the flanged design is to allow the wellhead to be assembled without twisting the heat trace cable and thermocouple wires around the inner pipe during well construction. The portals in the wellhead through which the inner pipe, heat trace cable, and thermocouple wires pass are sealed with rubber compression fittings.

The heat trace cable is an 8-mm diameter copper tube with two mineral-insulated copper conductors inside. It is rated at 4,500 watts (or about 12 watts per meter). The power to operate it is supplied by a portable, 5,000 watt, 240 volt AC, diesel generator.

4. INSTALLATION AND OPERATION OF SUB-PERMAFROST WELL

Upon completion of drilling the 380-m deep HQ corehole, a) the drill rods were removed, b) the footvalve assembly was screwed onto the bottom of the rods, and 350 m of rods were immediately re-installed in the corehole with the footvalve attached. The re-installation was done as rapidly as possible to prevent the corehole -- in which the water level was within about 15 m of the surface -- from freezing. As shown in Figure 3, the footvalve assembly had a casing bit attached to its end in the event it became necessary to wash the rods back down through ice or minor amounts of caving. Each 3-m joint of the drill rods was sealed with meltable resin to prevent water from entering the well through the joints. When 350 m of drill rods were back in the corehole, the string was clamped at the surface and allowed to freeze in place.

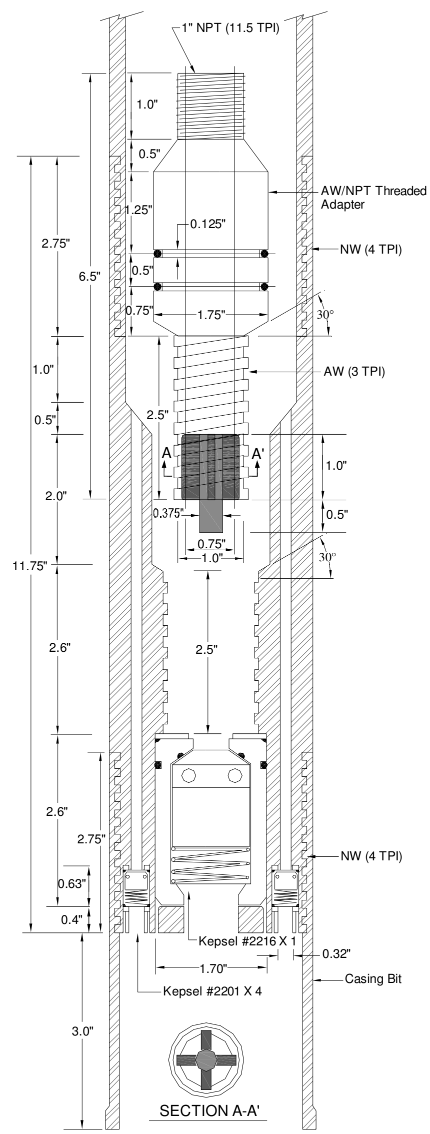

Figure 3. Details of footvalve

Subsequently, 350 m of nominal 1-inch (25-mm) schedule 80 steel pipe (the inner pipe) was lowered down inside the HQ rods, sealing each joint with Teflon thread compound. The heat cable was attached to the inner pipe at 3-m intervals using hose clamps and lowered together with the inner pipe. The thermistor wire, which was attached to the opposite side of the inner pipe from the heat cable, was also lowered simultaneously. One thermocouple was placed 3 m above the footvalve, and the second was placed 200 m further up (at a depth of 150 m) where the minimum borehole temperature was expected. The inner pipe, heat cable, and thermistor wires were routed through the wellhead. The adaptor at the bottom of the inner pipe has an adapter with AW box threads for screwing into the footvalve (and until the inner pipe was screwed in, the large check valve in the footvalve remained closed). The inner pipe was clamped at the wellhead when it was 1 m above the footvalve, and the drill rig -- which was in great demand -- was moved off site to continue other work.

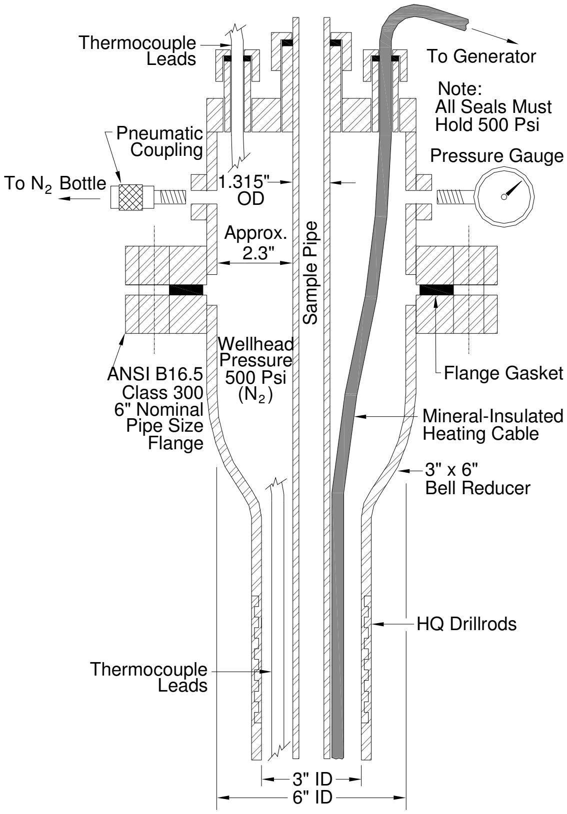

Figure 4. Details of wellhead

A 4-m high tripod was set up over the wellhead, and a 2,000 kg capacity cable hoist equipped with a digital scale was used to suspend the inner pipe. The scale enabled us to control the weight of the inner pipe against the footvalve assembly so that the inner pipe could be easily screwed into the footvalve. Before doing this, the heat cable was turned on for about 2 hrs to pre-heat the inner pipe so that water would not freeze inside it when the main central check valve in the footvalve was opened. The initial temperature of the inner pipe, measured by the thermocouples, was about -3 deg C; but after 2 hrs of pre-heating, the temperature was raised to between +10 to +20 deg C. When the inner pipe was screwed into the footvalve, the water level rose inside the inner pipe to a depth of 15 m below ground surface almost immediately, and the temperature dropped rapidly to about +5 deg C due to the formation water filling the inner pipe.

The digital scale was also useful in monitoring the expansion and contraction of the inner pipe in response to changing temperatures. The length of the inner pipe varied by almost 75 mm, shorter when cold and longer when heated. At this point, the two halves of the wellhead were bolted together since the inner pipe no longer needed to be rotated. The compression fittings on the wellhead were tightened to seal the inner pipe, heat cable, and thermocouple wires so that the wellhead and inner pipe could be pressurized. The wellhead and inner pipe had quick-connect pneumatic fittings which were attached via high pressure hoses to a compressed nitrogen cylinder.

The sub-permafrost monitoring well was pumped by airlifting using nominal 13-mm plastic tubing as an airline within the nominal 25-mm inner pipe. A small portable air compressor was used to supply the compressed air. The airlift assembly is shown schematically in Figure 5.

The hydraulic conductivity of the bedrock interval from 350-380 m was estimated from airlift recovery data following 4 hrs of pumping. The well had to be airlift pumped, however, for another almost 5 days at a rate of 15 L/min before a representative ground-water sample -- based on the measured electrical conductivity of the discharge reaching a constant value -- could be taken. While pumping with the heat cable ON, the thermocouple temperatures ranged from about +5 to +10 deg C. Although it was found that the heat cable could be turned OFF during airlift pumping and the thermocouple sensors remained slightly above 0 deg C, the heat cable was normally left ON during pumping to prevent any possibility of the well freezing. The heat cable was ON when pumping was stopped after taking the water sample, and the thermocouple temperatures again rose to about +10 to +20 deg C (the range of temperatures indicated by the two thermocouples).

After monitoring recovery again following the 5-day pumping for sampling, the wellhead and inner pipe were both pressurized to 500 psi with compressed nitrogen. This drove the water in the inner pipe back down below the base of the permafrost through the footvalve. Any water that might have accumulated in the annulus from leaks was driven out through the four smaller check valves. Once the well was pressurized, the wellhead was checked for leaks and the heat cable was turned OFF.

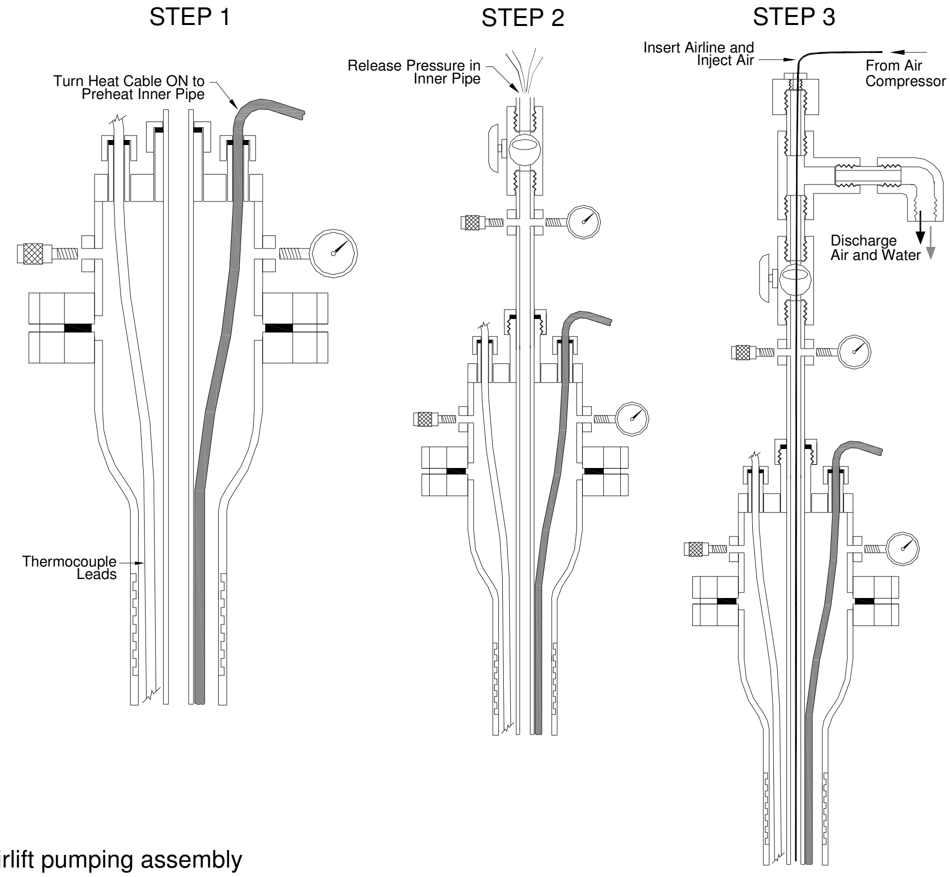

Figure 5. Airlift pumping assembly

5. SUBSEQUENT PROBLEMS

There were no detectable leaks in the wellhead at the time the wellhead was pressurized. However, over the next few days, the wellhead was found to lose pressure at a rate of about 5 psi per day; and the leakage rate became worse over time. Apparently some of the joints in the inner pipe, wellhead fittings, or possibly even the joints in the HQ rods were not completely sealed during the installation procedure. The wellhead pressure was “topped up” periodically while personnel were available, but the wellhead pressure eventually was not maintained. Consequently, water gradually rose inside the inner pipe and froze. An attempt to thaw out the well several weeks later failed. It is believed the inner pipe ruptured when water inside it froze. During the attempt to thaw the inner pipe, the heat trace was turned on; and when the ice plug in the inner pipe melted, the groundwater rose and flowed out through the rupture, filling the annulus between the casing and inner pipe. The wellhead was not pressurized during this operation, and the thermal output from the heat trace was not sufficient to keep the entire well from freezing (i.e., the heat loss from the inner pipe to the surrounding permafrost through the water-filled annulus and outer steel casing was greater than the heat output of the heat trace).

The main nitrogen leakages are thought to have been from the inner pipe joints and wellhead fittings. The pipe joints had straight, rather than tapered, NPT threads; and it is also possible that ice might have initially filled some of the thread roots during installation. Both factors may have prevented the joint sealing compound from properly sealing the joints. Similarly, the holes in the wellhead for the compression fittings had straight, rather than tapered, NPT threads; and ice in the threads was a possibility considering the weather conditions at the time of installation. The compression seals in the wellhead for the inner pipe, heat trace, and thermocouple wires could also be improved.

6. CONCLUSIONS

The newly designed sub-permafrost well functioned as intended except for the loss of nitrogen pressure over time. Hydraulic testing and groundwater sampling were successfully completed. If the inner pipe and wellhead fittings could have been made more air-tight, there is no reason that future sampling and monitoring could not have been conducted.

Possible solutions to the problem of maintaining pressure in the well include:

1) Welding the HQ casing joints (although it was never determined that the resin-sealed casing joints leaked).

2) Using tapered fittings on the inner pipe.

3) Improving the wellhead compression fittings.

One possible design change would involve filling the annulus with an environmentally acceptable antifreeze solution such that a much lower wellhead pressure could be used (making it easier to maintain the pressure). In fact, the hydrostatic formation pressure could be balanced with no additional wellhead pressure if a fluid of proper density were used. A problem inherent with this concept, however, is that the thermal output of the heat trace would have to be higher in order to raise the temperature of the entire well volume rather than just the inner pipe (and the insulating Thermos bottle effect of the air in the annulus would be lost). Another complication with this design change would be how to manage the fluid in the inner pipe and prevent its loss into or dilution with the underlying groundwater.

A potential modification could also be made to the footvalve. If the central check valve could be opened or closed at will, pressure or a balancing fluid above the valve would not be needed to keep groundwater below the base of the permafrost. The valve could be operated electrically by a solenoid or by a hydraulic or pneumatic circuit.

7. ACKNOWLEDGEMENTS

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