FEATURES OF PLANNING A DETAILED STUDY OF THE HYDRODYNAMIC AND HYDROCHEMICAL PROPERTIES OF THE YENISEISKIY SITE OF THE NIZHNEKANSKIY MASSIF

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In the coming years, construction of an underground research laboratory will be started at the Yeniseiskiy site within the Nizhnekanskiy rock mass. In this regard, arranging for subsoil monitoring is seen as a priority task to identify the required parameters of undisturbed rock mass. Specific features of hydrogeological setting within the rock mass at the Yeniseiskiy site necessitate interval monitoring in deep wells with open holes using multipacker systems. In-depth studies of sections with a discreteness of 1—2 m are required to identify the monitoring intervals. However, Russia has no hands-on experience in this matter. The article discusses international practice of detailed research at analogue facilities and describes the equipment used. Interpretation of the data obtained is seen as an important part of the research with relevant technique associated with interval injection at constant pressure being discussed in the article.

Keywords: *radioactive waste, underground research laboratory, hydrogeological and hydrochemical conditions, subsoil monitoring, interval studies in wells, multipacker systems, differential flow metering, interval injection.*

The studies included into the strategic master plan aiming to demonstrate the safety of deep RW disposal facility construction, operation and closure in the Nizhnekanskiy rock mass (Krasnoyarsk Territory) involve a great amount of work which will be done to explore and characterize the Yeniseiskiy subsoil site, including the area potentially affected by the DDF RW. Specific focus has been placed on the exploration of hydrodynamic and hydrochemical conditions of the massif that are essential for any forecasts regarding the long-term disposal safety.

A large amount of work addressing this area of research was performed at the Yeniseiskiy site in 2003—2014 under the appraisal and prospecting stages of geological exploration. During this period, 24 wells reaching a depth of 100 to 700 m were drilled on the site. Some of these wells penetrate the target horizon envisaged for RW disposal. To date, 8 deep wells out of 12 that have been initially drilled remain on the site, the rest have been abandoned or are to be abandoned due to their inadequate technical state.

Previous efforts on groundwater inflow testing have revealed certain heterogeneity as regards the hydrogeological properties of the massif along with very low permeability of the rocks. From a hydrogeological point of view, both laterally and sectionally, the rock mass is characterized by a block structure with no or hindered hydraulic connection between the blocks. Therefore, groundwater heads in different parts of the section and at the same elevations in the plan differ by tens of meters. The general trend in the distribution of pressures noted in [1—3] indicates their decrease with depth, which implies the downward groundwater flow.

However, based on the results of actual data processing, no unambiguous statement can be made regarding the pressure decrease with depth since, on the contrary, in some of the wells the pressure increases with depth (Figure 1). These data emphasize the thesis about the hindered or absent hydraulic connection between the individual blocks in the rock mass. Data shown in Figure 1 were obtained during studies covering rather long intervals of 50 m: each of these intervals could include several elements of the geological structure and zones of increased permeability, the thickness of which could vary from 0.2 to 13 m [4]. Thus, zones with different heads could be assumed within the study intervals.

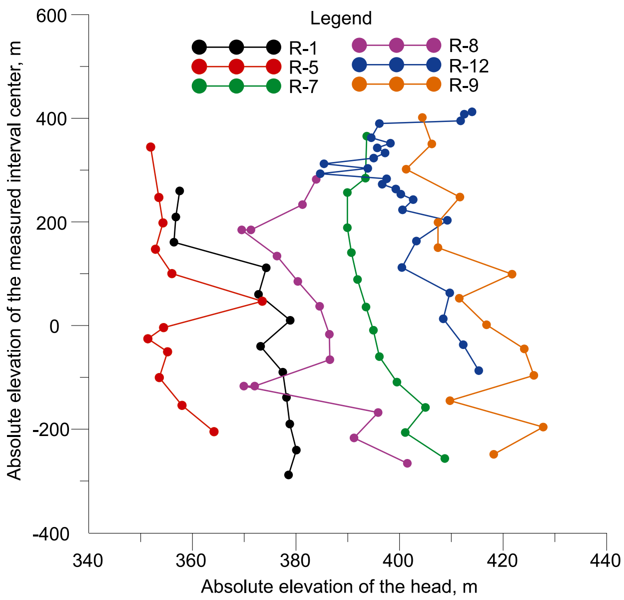


Figure 1. Distribution of heads along the depth in the wells of the Yeniseiskiy site

Specific hydrogeological feature was noted in [1—3] suggesting no relationship between the modulus of fracturing and the filtration coefficient of rocks, which seems to be inconsistent with the results of detailed studies performed at analogous facilities abroad [5] and resulted from data averaging over long intervals.

Uncertainties in the distribution of heads along the wellbore and increased permeability zones manifest the need of detailed hydrogeological studies seeking to arrange rock mass monitoring system ahead of URL construction which is viewed as a key goal. Common groundwater monitoring approaches are incompatible with some specific features of rock massifs with differing pressure heads along the section. Namely, when the wellbore connects individual rock blocks hydraulically causing crossflows from one block to another due to different pressure heads. In this case, the intensity and direction of the flows remain unknown. Under such conditions, the water level established in the wellbore appears to be an average value not attached to any interval, thus, its values cannot be used in forecast calculations.

For the same reason, interpretation of the data from the testing of water samples taken from a single wellbore is impossible even if the sampling conditions were met. In such cases, it remains unknown whether the sample belongs to one or another interval of the section, which is unacceptable given the importance of hydrochemical testing aimed at demonstrating the long-term safety of RW disposal.

Monitoring within any interval of the well provided the isolation of the rest of the wellbore suggests that such an interval cannot be selected without prior detailed studies of the section. Therefore, for monitoring purposes, a unified approach based on interval monitoring using multipacker systems has been implemented at analogue facilities abroad [5—7]. These systems allow simultaneous monitoring of up to 8 intervals in one well, therefore, their installation is preceded by detailed studies of the section suggesting considerable discreteness to determine the monitoring intervals.

At the Yeniseiskiy site, interval monitoring could and should be implemented using already available deep wells. Interval monitoring is considered particularly important at URL pre-construction stage allowing to study the initial state of the rock mass, including the background indicators of the groundwater quality. In this regard, detailed studies of sections in the existing wells selected for interval monitoring purposes is viewed as a top-priority task. Such detailed studies aim to identify the zones and individual fractures with the highest permeability and to determine the water permeability in these zones, to study the distribution of pressure heads in the section providing sufficiently detailed information for qualitative identification of flow zones and their directions (into the well or from the well). The latter circumstance greatly affects the decision-making on the hydrochemical sampling intervals, since it makes no sense to take samples from the intervals subject to water inflow from the well.

Since no interval studies of hydrogeological properties focused on low-permeability rock mass with a discreteness of 1—2 m have been previously implemented in Russia, we should use international experience as a reference one. Reports developed by Posiva (Finland) and SKB (Sweden) are considered as sources of most ample information on the methodology and results of detailed studies considering geological and hydrogeological conditions being similar to those found within the Nizhnekanskiy rock mass.

Posiva (Posiva Oy and Posiva Solutions Oy) and SKB (Swedish Nuclear Fuel and Waste Management Company) are involved in the exploration and comprehensive study of promising sites for underground RW disposal, monitoring, and long-term safety assessment of underground RW repositories. For the first time ever, Finland was able to get a license for RW disposal in the ONKALO DDF RW to be constructed at the Olkiluoto site (2016). A URL was built in Sweden at the Forsmark site, which was selected for DDF RW construction, all required R&D complex was completed with the license application for RW disposal currently being reviewed by the Swedish government.

In Finland, rock masses have been studied since the 1980s with new methods and areas of well research that evolved in mid-late 1990s due to the establishment of the Posiva company (1995). The geological structure of candidate sites for RW disposal in Finland is similar to the one of the Nizhnekanskiy rock mass. The Olkiluoto site section comprises metamorphic rocks mainly presented by gneisses of various compositions with intrusions of granite pegmatoids and diabase dikes [9]. The section has been studied to a depth of some 1,000 m. Differential flow metering and interval injection under constant pressure are considered as the main methods applied during the detailed studies in the wells.

Hydrodynamic research

Differential flow metering method

The differential flow metering method and the applied equipment was developed by a small geophysical company PRGTec Oy, which was subsequently contracted by Posiva to perform some work at its facilities [10, 11]. The method was called Posiva Flow Log (PFL). Differential flow metering differs from traditional flow metering methods used in borehole geophysics since it allows to measure small and ultra-low flow rates through the application of a thermal pulse method developed by the US Geological Survey in the 1980s.

Downhole tool is fitted with a flow sensor featuring three vertically oriented thermistors with the middle one serving as a source of thermal pulses and the two adjacent ones recording the propagation of temperature front, the parameters of which depend directly on the flow rate. Two end thermistors also allow parallel study of the flow direction.

This tool (Figure 2) allows discrete interval measurement of fracture hydrodynamic parameters in isolated intervals of an open wellbore with the interval itself being sealed by elastic rubber disks. Unlike expandable packers, the use of rubber disks provides significant reduction in the measurement time at one interval with force effects prevented due to the expanding force of the packers acting on the wellbore walls in the vicinity of the measured interval. If no large-size caverns are present on the borehole walls, rubber disks provide the required interval isolation which is also due to the fact that the heads in the insulated interval and in the wellbore are equal provided the main water flow bypassing along the borehole.

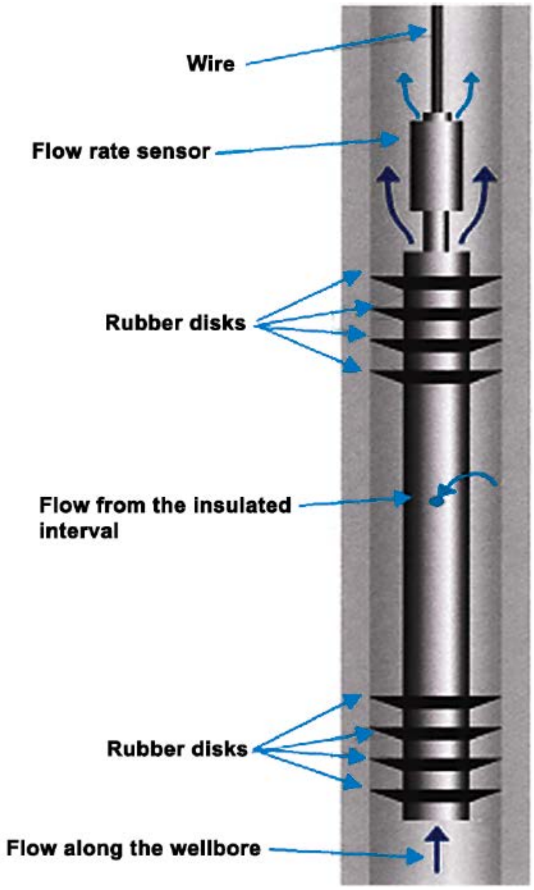


Figure 2. Differential flow measurement device

In addition to the flow sensor, the device is equipped with pressure and temperature sensors, a sensor designed to measure the specific electrical conductivity of water and a current logging electrode.

The downhole tool allows to address the following key tasks:

- to map all conductive cracks and to measure the water rate in them;
- to identify the water flow direction (into the well or from the well);
- to measure the distribution of heads in the wellbore;
- to identify (calculate) fracture filtration coefficients;
- to identify the water temperature distribution in the well;
- to measure the electrical conductivity of water in cracks;

• to dissect the rocks in the section by current logging method.

The tool attached to a multicore geophysical cable is lowered into the well. The winch is fitted with some mechanical and optical tools allowing to monitor the depth to which the tool is lowered. Since current logging provides a high accuracy in capturing the boundaries of various rocks, these boundaries are considered as additional marks used to specify the location of the tool in the borehole, which is important for a series of sequential measurements assuming different parameters.

Table 1 summarizes some important characteristics of the device for differential flow metering.

Flow measurements provide for stepwise advancement of the device from the bottom to the top. At each interval, the device is stopped and, after flow rate stabilization, is moved to the next interval. The measurement time at one interval depends on the flow rate and can amount to 10—15 minutes.

The study is performed in two stages. At the first stage, the device is moved along the wellbore under static conditions. At this stage, intervals of water absorption from the well are identified. At the second stage, a fixed depression is established, usually 10—20 m, and the measurements are repeated.

Figure 3 shows the way in which the measurement results are presented.

Table 1. Instrument specification sheet

Parameter	Value
Borehole diameters	56, 66, 76 mm. Can be applied in large diameters wells
Investigated well depth	Up to 1,500 m
Length of the insulated interval	0.5–2.0 m
Measured flow rates	0.1–10 ml/min (thermal impulses), 2–5,000 ml/min (constant heating)
Pressure sensor allowing the measurement of a static level in the interval	Druck 1830, 200 kPa, accuracy ± 0.1 %
Temperature sensor	0–40 °C, accuracy ± 0.1 °C
Electrical resistance sensor	0.2–100 cm/m, accuracy ± 5 %
Electrical resistance of the rocks (current logging)	1–100,000 Ohm
Identified parameters	Filtration coefficient, head in intervals, orientation of the absorbing cracks

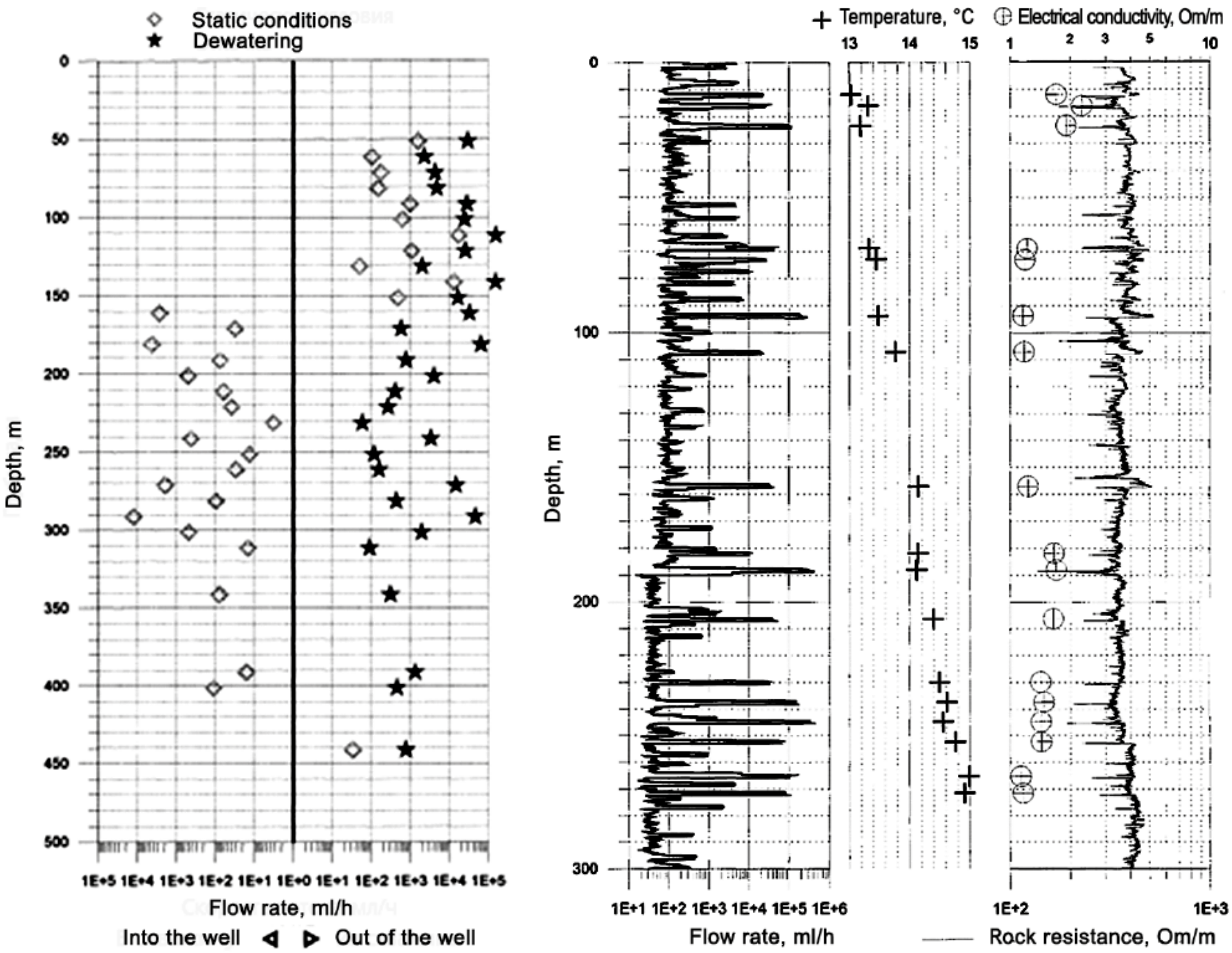


Figure 3. Results from the differential flow metering

The PFL method has been also widely used at SKB facilities. Studies are carried out in shallow and deep wells, and they are repeated in case of any alteration in the parameters recorded by multi-packer monitoring system. In most deep wells, PFL results are duplicated by interval injection at constant pressure, since the latter method allows more accurate permeability measurements in the intervals.

Interval injection method

The interval injection method known as HTU (Hydraulic Testing Unit) and the equipment applied was developed by Geopros OY engaged in Posiva research. The equipment was designed to measure the hydrodynamic parameters of the rock mass in deep wells (Figure 4) [12].

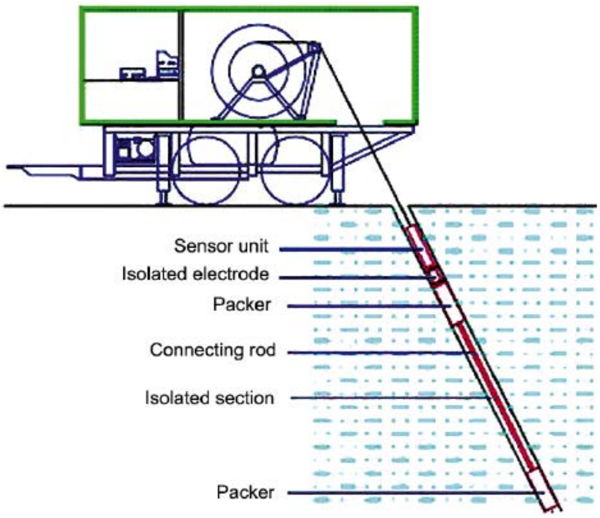


Figure 4. HTU equipment for interval injection

The downhole part of the equipment includes a double packer, a sensor unit and an electrode for current logging. The sensor unit includes 3 pressure sensors that monitor the pressure in the section, above and below it, temperature sensors and possible leaks in the discharge line. The sensor unit also features an active pressure regulator. Water is injected into the section through a 14/10 mm polyamide tube, water is supplied through the second 10/6 tube to expand the packers. The insulated current log electrode is an auxiliary element allowing to spot the depth of the packers. The tubes and signal wires are located within an umbilical sleeve, the outer sheath diameter of which accounts for 34.4 mm.

At the surface, the equipment is housed in a trailer installed on the chassis of a standard logging station. It includes a winch, a unit involving four automatically connected flow meters, a compressor and a pressure vessel with water. Water is pumped from a 500-liter pressure tank by compressed air into the interval.

HTU equipment was designed to test the wells reaching a depth of 1,020 m with a minimum diameter of 56 mm. The standard length of the measurement interval accounts for 2 m. If necessary, it can be increased by building up an inter-packer rod. Filtration coefficients can be measured in the range of 10—10^{-6} m^3/day, measurable flow rates range from 3.6 ml/h to 468 l/h. The depth of the packers is controlled by markers applied to the umbilical sleeve after 1 m, as well as markers of a more contrasting color applied after each 25 m. In addition, the winch is fitted with a sleeve length counter.

Hydrodynamic parameters of the interval are identified based on the interpretation of data obtained from the injection performed at a constant head pressure. Therefore, the most important function of the installation is to maintain a constant pressure. Depending on the filtration properties of the interval, two methods allowing to maintain such a constant pressure are used under studies. At medium and relatively high values of the filtration coefficient, an active pressure controller installed above the upper packer and controlling the pressure drop upstream in the discharge line is activated. It operates quite accurately in case of no noticeable water flow through it.

If the pressure drop in the discharge line is too big, the pressure control becomes unstable. Thus, the initial pressure in the pressure vessel from where the water is supplied to the discharge line is of great importance. The pressure in the tank is set before the water is injected into the section: the pressure level is specified by the operator based on previous experience. In many cases, the nature of the pressure stabilization in the section following packer expansion gives the operator some insights on the possible value of the filtration coefficient based on which the operator can set the initial pressure in the pressure vessel.

Figure 5 presents a typical injection curve for an interval.

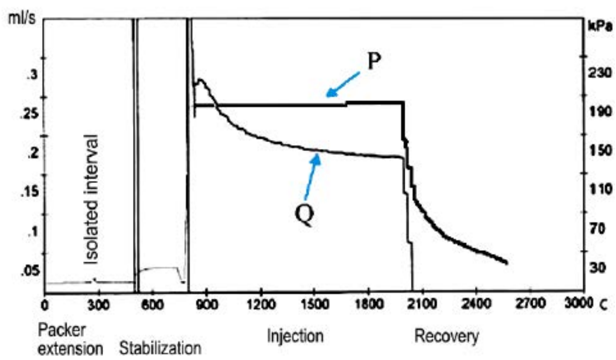
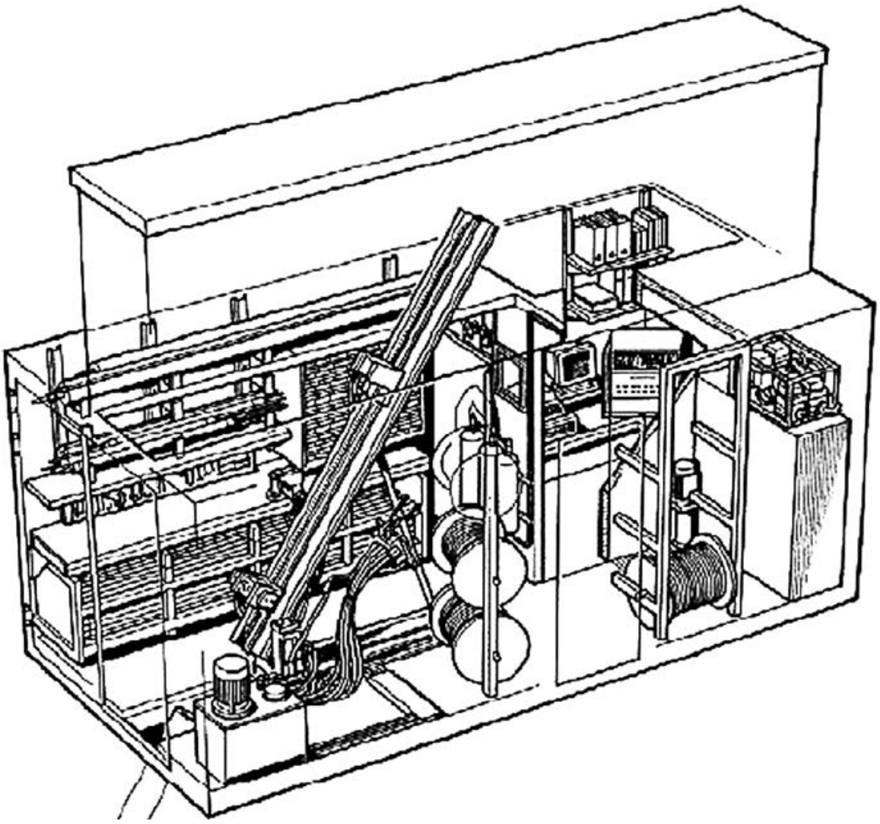


Figure 5. Typical injection curve for a constant pressure interval



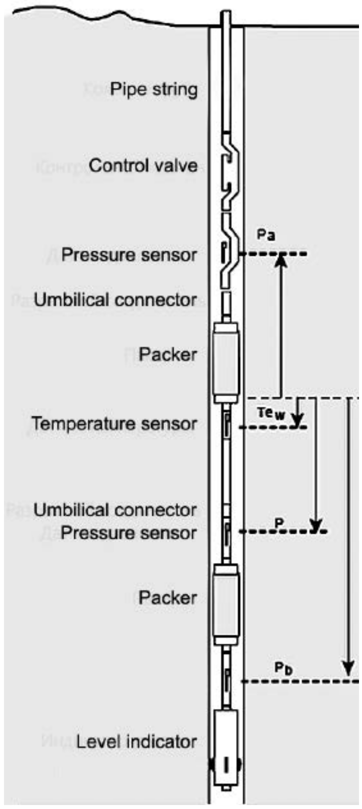


Figure 6. Layout of an installation for PSS interval injections

The interval injection method is the main method for detailed studies of rock massifs applied by the Swedish company SKB, whereas differential flow measurement is used less often, since it requires the involvement of experts from Finland. Unlike HTU equipment, the double packer is mounted on an aluminum pipe string having a diameter of 33/21 mm with double-sealed steel threaded connections. The installation itself and the method applied were called PSS (Pipe String System) [13]. There are several equipment modifications — PSS-2, PSS-3 without any specific differences. The layouts of the surface and downhole equipment are shown in Figure 6.

The launching mast can be installed at any angle to the vertical providing the operation in deviated wells. All equipment is housed in a steel container with a collapsible covered superstructure designed to lift the mast and a cut-out in the floor for its installation above the surface casing of the well.

The installation can support a maximum load of 2.2 tons. The container is divided into 2 compartments: one of which contains the assembler, pipes, three drums for multicore cable and polyamide tubes allowing to steer the control valve and packers, a pressure vessel, a pump, flow meters and other equipment, and the second contains a computer and a control panel for packers and control valves. The expansion of the packers occurs due to the impact of water from the pressure vessel, the test valves are solenoids controlled by the data acquisition system software.

The interval water injection system includes a water tank, a pump and flow meters. At low flow rates, water is pumped into the interval using a pressure vessel connected to an inert gas cylinder through a pressure regulator. The downhole equipment includes three pressure sensors located between, above and below the packers, and a temperature sensor. Purpose-designed loose connections are installed on the pipe string, the breaking force of which is lower than that of other threaded connections. In the event of packers stuck in the well this allows to extract the pipe string and part of the downhole equipment. The end element is the diving depth indicator.

The standard filling procedure includes the following steps:

1) the tool is lowered to a specific interval;
2) packers expand;
3) pressure is stabilized after the interval has been sealed;
4) preliminary impulse filling occurs;
5) injection at a constant pressure;
6) pressure recovery;
7) relieving pressure in the packers, moving to the next interval.

Preliminary impulse filling allows qualitative assessment of permeability in the investigated interval. For these purposes, after the pressure has stabilized, the control valve on the pipe string in front of the upper packer is closed, the pipeline is evacuated with a buildup of an excess water pressure of 20 m above the static one. The valve opens and level recovery is monitored. If the level recovery is less than 50% in the first 10 minutes, the interval is considered as of a low permeability and no further water injection at a constant pressure is performed, the recovery process is subject to continued monitoring. If the interval appears to be more permeable, the next step involves water injection at a constant overpressure of 20 m and under flow rate control, which lasts about 20—30 minutes. The check valve is closed and the pressure build-up is recorded.

The investigated intervals have standard length accounting for 100, 20 or 5 m depending on the permeability and available knowledge about the section in the well. Testing time for one interval ranges from 105 minutes (100 m) to 70 minutes (20 and 5 m) [13].

Interval injection interpretation

Interval injections are widely used to study the water permeability of rocks by hydraulic engineers in Russia and are even regulated by GOST provisions [14]. Basically, these studies commonly result in the identification of specific water absorption - a qualitative parameter that can help to identify zones of increased permeability, but appears to be insufficient for making any forecasts. When the filtration coefficient can be determined, approximate dependences established for a stationary mode are used taking no consideration of the experimental background and the recovery period. The Swedish company SKB has developed an interpretation technique providing the application of transient injection and recovery results.

The simplest case suggests a constant pressure injection into an interval corresponding to an isolated fractured zone of a large size (the planned dimensions of the zone are much bigger than the radius of influence). This problem has been solved by Jacob and Logman [15]. They also showed that given relatively short duration of the experiment, the solution for a well with a given head (pressure) can be approximated by the Theiss formula, the logarithmic approximation of which in this case can be calculated as follows:

$$\frac{H}{Q(t)} = \bar{H} = \frac{1}{4\pi T}(\ln\frac{t}{r_w^2} + \ln 2,25a), \qquad (1)$$

where H is the excess head in the investigated interval, $Q(t)$ is the injection flow rate varying during the experiment, T and a stand for water permeability and piezo conductivity coefficients in the investigated interval, respectively, r_w is the well radius, t is the time elapsed from the start of injection. To interpret the dependence (1), graphical-analytical method is used. On the graph $\bar{H}$, $\ln(t/r^2)$, the experimental data fall on a straight line with the slope coefficient of $C = \Delta\bar{H} / \Delta \ln(t/r^2)$ based on which the water permeability $T = 1/(4\pi C)$ and elastic capacity $S = 2,25T(1/r^2)$ can be calculated. $(1/r^2)_0$ stands for the point of graph intersection with the $\ln(1/r^2)$ axis.

In a more complex case, suggesting some resistance in the near-wellbore zone (for example, due to the drilling method applied), the Hurst, Clark and Brauer solution is used [16]. The solution to this problem is obtained in Laplace images, and its use requires inverse transformations, which are implemented using the AQTESOLV software [17] together with the least-square method.

Log-log plot (Figure 7) presents an example showing how the results of experimental injections can be interpreted using the AQTESOLV software. Figure 7 shows two graphs, one of which is the time tracking one $\bar{H} \div t$ (blue dots), the other (black dots) $\frac{\partial \bar{H}}{\partial \ln t} \div t$ is the diagnostic one.

Based on the shape of the curve, a model and a calculated relationship can be selected allowing the interpretation of the test injections. The horizontal line in Figure 7 corresponds to an isolated interval. If the interval is not isolated, but is associated with an adjacent one, the shape of the diagnostic curve

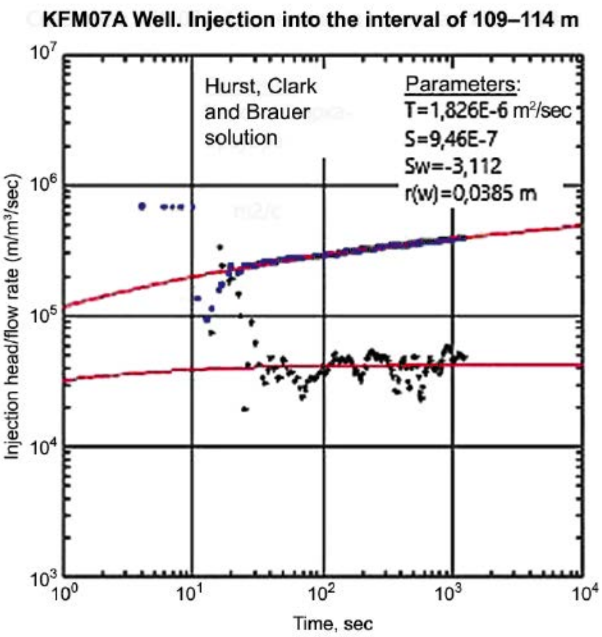


Figure 7. Interpretation of results considering the case of injection into an isolated fractured interval using the AQTESOLV software.
Blue dots — time tracking, black dots — diagnostic graph

has the shape shown in Figure 8. The solution for this case was obtained by Hantush [18].

For the case of vertical crack isolation, the diagnostic curve looks like a line running at an angle of less than 45 ° (Figure 9). An analytical solution for constant pressure injection into a vertical fracture was obtained by Ozkan and Raghavan [19].

Recovery period is considered as a specific feature in the interpretation of injections performed at a given pressure. During this period, constant pressure is no longer maintained in the interval and the boundary condition in the well changes. Thus, the injection process is interpreted based on the Hantush solution with a constant pressure, whereas the recovery — based on the same Hantush solution, but with a constant flow rate.

Following the injections into different intervals and their interpretation, the data obtained for each well is compared. The main result of this research is the identification of intervals with increased filtration properties, which is required for subsequent hydrogeological modelling.

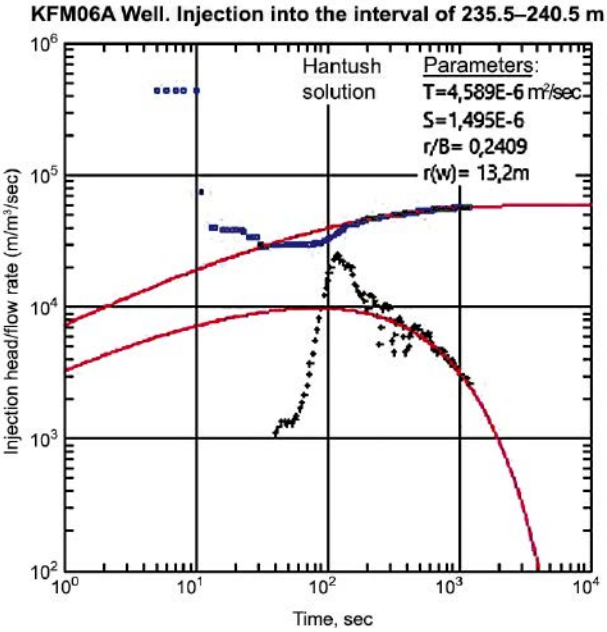


Figure 8. Interpretation of results considering the case of an injection into a fractured interval connected with an adjacent one. Hantush's scheme.
Blue dots — time tracking, black dots — diagnostic graph

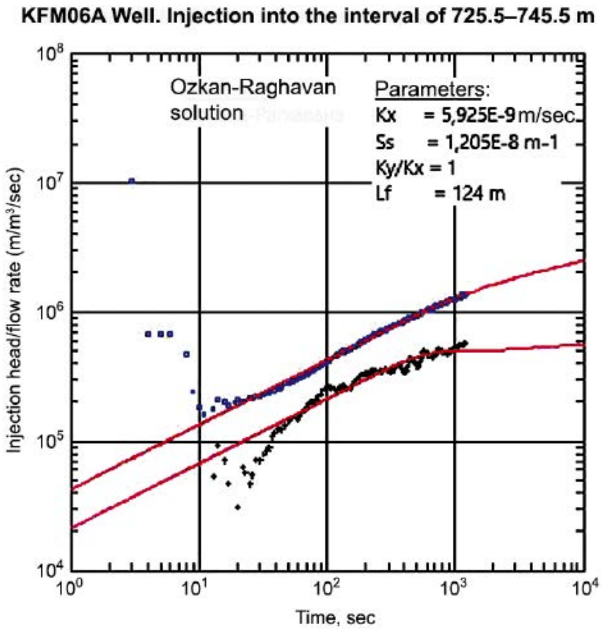


Figure 9. Results of vertical fracture injection interpretation.
Blue dots — time tracking, black dots — diagnostic graph

Hydrochemical research

Hydrochemical monitoring is believed to be a most important element of the entire monitoring system at underground RW disposal facilities, since groundwater is the main substance capable of carrying radionuclides from the disposal system to the terrestrial biosphere. In addition, potential risk of corrosion attack on the materials of containers and engineered barriers depends on the groundwater quality in the target interval. Particular importance is paid to the selection of hydrochemical monitoring intervals, which is seen as a main task of preliminary detailed studies performed in the wells.

Water inflow into the well, rather than its outflow is considered as the main criterion providing the selection of hydrochemical monitoring intervals. Intervals of water inflow into the well can be easily identified by differential flow metering also allowing for a simultaneous identification of a specific water permeability profile in different intervals. Water permeability, flow rate and flow direction can be evaluated, thus, the hydrochemical monitoring interval can be selected more easily.

If differential flow measurement is not possible, hydrochemical monitoring intervals can be selected based on the evaluated head profile in the well — the intervals with the highest heads are of interest. If the heads are equal in several intervals, the interval with the highest water conductivity is selected. At analogue facilities operated abroad one well usually involves no more than two intervals selected for hydrochemical monitoring purposes. Moreover, these intervals remain the same for the entire monitoring period. The only exception is the case of noticeable pressure redistribution in the well due to various actions in the underground structure.

At the stage of detailed studies, of particular importance is the identification of the background groundwater quality indicators. Absence of indicator substance in the samples (fluoresceine, which is always added to the flushing water during well drilling) is considered as a criterion for the pumping out of the formation water from the interval. The application of fluoresceine as an additive to the drilling water is a requirement specified in the internal regulations of Posiva and SKB, which is associated with the seepage of the drilling fluid into the permeable zones of the formation during well drilling. Later, during the interval dewatering, drilling fluid is the first one to show up, and the absence of this indicator in the samples is seen as the criterion suggesting its complete removal. However, even if the indicator is not found, the pumping can continue for a long time until any alternating water quality indicator gets stabilized.

Given the low water flow rates in the intervals, pumping can take several days prior to sampling. Hydrochemical monitoring experience gained by Posiva and SKB shows that the generally accepted criterion assuming a minimum pumping volume required for sampling and amounting to 3—5 interval and pipeline volumes is considered sufficient only in rare circumstances. In most cases, much larger volumes have to be pumped out to take a representative sample [20, 21].

Since no indicators are present in the drilling fluids during drilling and expansion of deep wells at the Yeniseiskiy site, the task of identifying sufficient volume of liquid pumping from the intervals before sampling becomes more complicated. In such cases, it seems useful to analyze the samples of water used as a flushing fluid. Apparently, required is a long-term pumping of water from the intervals provided the monitoring of rapidly changing water quality indicators with the stabilization of some of them that can be viewed as a sampling criterion.

Diaphragm pumps purposely designed to allow the sampling from small diameter wells are applied to dewater the intervals (Figure 10). The pump consists of two cylinders one of which is located inside the other, the outside part of the inner cylinder is perforated. Each of the cylinders is attached to its own polyamide tube with a diameter of 8—10 mm. The tube of the inner cylinder is used to supply the compressed air; water is displaced from the cavity between the cylinders into the second tube. The cavity between the cylinders is equipped with a check valve at the bottom, the second check valve is installed at the inlet to the water supply tube. When the pump is lowered below the water level, the space between the cylinders and the supply tube is filled with water from the interval. Air is injected into the inner cylinder, expanding the membrane and displacing water from the intercylinder space into the water supply pipe. At this moment, the check valve at the inlet to the cavity

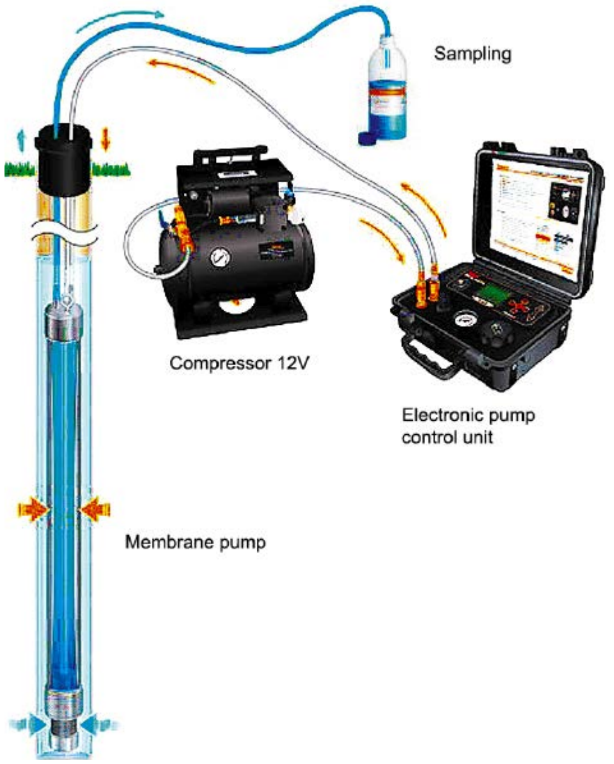


Figure 10. General layout of the diaphragm pump and its control elements

between the cylinders closes, and the upper check valve opens. When the air pressure is released, the upper valve closes, and the lower one opens, water fills the cavity between the cylinders. Then the cycles are repeated. Pump control is automated. The pumps have diameters of 25—40 mm and are capable of pumping water from a depth of 150 m with a capacity of 10—100 l/h.

The sampling equipment involves a double packer, the inter-packer interval of which is connected to a polyamide tube with a diameter of 8—10 mm, which in turn is connected to a plastic 40—50 m-long tube with a diameter of 30—50 mm, which emerges at the wellhead. A diaphragm pump is lowered into a plastic tube to pump out the water from the interval. The polyamide tube applied to connect the interval with the pump significantly reduces the volume of water in the "interval — wellhead" system and, accordingly, the volume of the pumped water.

Posiva and SKB apply similar approaches to the identification of hydrochemical monitoring intervals and quite similar pumping equipment, only the downhole equipment differs. Since 1997, for sampling purposes, Posiva has been using PAVE (Pressurized water sampling equipment) providing simultaneous sampling of up to three water samples from one interval of 100—150 ml each under the pressure of the sampling point, which is important for analyzing the gas composition of water [22].

At SKB, a container fitted with selective Eh, pH sensors, as well as conductivity, pressure and temperature sensors is installed above the diaphragm pump. Above it, a flow sampling cylinder is installed that can be closed from the surface. The equipment is lowered on an umbilical sleeve that provides all necessary communications with the wellhead [23].

Findings

Since the URL construction at the Yeniseiskiy site is about to start in the coming years, subsoil monitoring and the arrangement of relevant systems in the near field of the constructed facility becomes particularly relevant. International monitoring practice under similar conditions is based on multizone observations using multi-packer systems, which is due to the fragmentation of hydrogeological blocks in the section. Monitoring intervals in each well are selected based on detailed studies with a discreteness of up to 1—2 m.

Detailed studies are performed using exclusive nonpareil equipment designed specifically for these purposes. Since the design development and manufacturing of similar equipment in Russia is going to take a lot of time, possible application of available standard equipment should be considered at the initial stage of research. The first top-priority task is to arrange for multi-zone monitoring of the existing wells in 2021 using available standard equipment.

Out of all the above-mentioned methods implemented at analogue facilities abroad at the stage of detailed studies, interval injection at a constant pressure is considered as a most accessible one that can be potentially applied at the Yeniseiskiy site. Detailed studies will require a double packer with a variable inter-packer distance, a high-pressure pump providing water injection into the packers, a set of polyamide pipes, low-flow meters, pressure maintenance devices, etc. To allow the research in a wide range of intervals, the packers are required to be mounted on pipes using a hoisting mechanism with an appropriate lifting capacity.

As part of detailed studies, hydrochemical sampling of intervals identified for these purposes is a must. Therefore, the packers can be mounted on a pipe string provided that the interval between the packers is communicated with the surface using polyamide pipes and the pipe volume is sealed. A more practical option suggests the installation of a packer string on a cable of a logging station with its winch allowing to control the run depth. Diaphragm suction pumps are also available in the Russian market.

In the coming years, under the detailed studies performed some specialized organizations should be chosen to design and manufacture the equipment similar to the one being widely used by Posiva and SKB. First of all, a differential flow meter should be manufactured since it can greatly facilitate the detailed studies on the identification of multi-zone monitoring intervals, which is viewed of decisive importance for the long-term safety demonstration.

Conclusion

1. Transition to multi-zone monitoring of intervals with the highest water permeability is required due to the specific features of hydrogeological conditions at the Yeniseiskiy site of the Nizhnekanskiy rock mass.
2. Detailed hydrodynamic and hydrochemical studies are required to identify the monitoring intervals in each well. Interval injection at a constant pressure with a discreteness of up to 2 meters is considered as the most accessible detailed research method.
3. Hydrochemical studies performed in the intervals with the highest heads to determine the background water quality indicators are seen of a particular importance.
4. Interval injection is considered as the most reliable way allowing the identification of increased permeability intervals within the rock massifs, which is required for the development of predictive models used for disposal safety demonstration purposes.

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