EVALUATION OF APPROACHES FOR WELL ABANDONMENT AND TEMPORARY SHUTDOWN AT THE YENISEISKIY SITE (KRASNOYARSK TERRITORY, NIZHNEKANSKIY MASSIF)

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Rock mass is considered as a natural barrier impeding the release of radioactive waste into the environment, being part of a multi-barrier system designed to ensure the safety of deep disposal facilities for radioactive waste (DDF RW). A number of regulatory documents [1] and recommendations [2, 3] states the importance of the geological medium, namely, its characteristics for the long-term safety of RW disposal. Current stage of URL development project specifically focuses on providing the opportunities for geological research covering target RW disposal horizons solely via borehole methods before the entire complex of underground excavations is formed. Due to long-term operation of wells and their initial design features, the state of some of these wells has appeared to be unsatisfactory requiring reconstruction. In addition, in accordance with certain legislative requirements, all wells shall be abandoned after relevant operations are completed. The article discusses the reconstruction and abandonment of wells drilled at the Yeniseiskiy site. It demonstrates the feasibility of proposed designs providing the opportunities for further expansion of studies to investigate the state of rocks under natural conditions and to arrange for monitoring. The paper provides an evaluation and comparative analysis of plugging materials proposed to be applied under well abandonment operations.

Keywords: *radioactive waste, temporary shutdown of wells, rock mass characterization, well plugging methods and materials, well designs, underground research facility.*

Current stage of URL development project implemented in the Nizhnekanskiy rock mass [4] suggests that geological exploration at the target horizons envisaged for radioactive waste disposal can be performed using borehole methods before the complex of underground excavations is formed. In this regard, the wells available within the Yeniseiskiy area that were drilled during the prospecting and appraisal stage of exploration are considered of a particular importance. At previous stages during the geological study of the site, 24 wells were drilled to a depth ranging from 100.0 to 700.3 m. The depth of drilling operations in 2003—2010 and 2010—2014 totaled some 11,611 m.

Regulatory requirements in the field of subsoil use, as well as the terms of subsoil use at the Yeniseiskiy site, provide for the abandonment and temporary shutdown of wells completed during the previous stages of geological exploration [5]. Well abandonment measures provide for well upgrading to ensure the preservation of subsoil and environmental protection. Temporary shutdown suggests that the wells may be suitable for further use, in particular, for additional studies and long-term hydrogeological monitoring.

Since more precise information on hydrogeological and hydrogeochemical conditions should be further collected, in particular considering the target depth interval, and a long-term monitoring system covering some of the existing wells in the Yeniseiskiy area (Figure 1) should be arranged, temporary shutdown of the wells seems to be quite a feasible option. Re-examination of the wells and control measurements of their depths performed using level gauges of the USK TL-750 type in 2017—2018 revealed that certain difficulties can be faced during the research in the potentially suitable wells. The depths of the wells do not correspond to the primary drilling data. Thus, a complex of recovery and maintenance operations (reconstruction) will be required during the temporary shutdown of the wells.

Regulatory requirements [6, 7] as well as commonly applied well reconstruction approaches were evaluated and it was found that they do not consider the specific features of the facility being developed at the Yeniseiskiy site, and are focused on fundamentally different geological and hydrogeological features of rock masses. Obviously, this will negatively affect both further R&D and the results obtained. Also, additional risks may be posed suggesting that the insulating properties of the geological environment can be breached.

Thus, the use of standard well reconstruction methods providing for the installation of a metal casing string and a filter in the interval from the wellhead to its bottom followed by cementation of the supra-filter column (Figure 2) will essentially obstruct further operation on well abandonment. Whereas the availability of the casing in the studied areas of the massif renders impossible further comprehensive studies in the wells using modern methods and tools.

Furthermore, the complexity of the geological section and the hydrogeological features of the massif do not allow simultaneous identification of the intervals corresponding to most permeable rocks which is required to arrange for long-term observations. Casing strings and filters thought to provide separate testing of aquifers in the target and overlying intervals will cause the overflow of water from the disturbed zones along the annulus (Figure 3). Water from different horizons will be mixed causing the averaging of the samples, thus, it will be impossible to identify whether the water belongs to a specific interval.

Hence, standard technical methods for well reconstruction had to be reconsidered allowing their further application. Therefore, features of hydrogeological conditions within the rock mass were evaluated and the actual state of the wells was investigated.

The prospecting and appraisal stages of geological exploration at the Yeniseiskiy site have revealed quite complex hydrogeological conditions within the entire exposed section (Figure 4). The subsoil massif having very low permeability within the target horizon and adjacent parts of the section is characterized with a block structure of water-conducting fracture zones with either zero or hindered water exchange between them. Thus, the groundwater heads in different parts of the massif can differ quite significantly, namely by more than 50 m, which, in turn, can result in some water flows between the blocks along complex fracture systems. In this regard, considering the long-term safety of the deep disposal facility these possible filtration paths are a key point of interest. Therefore, during the planned R&D, intensive interval studies with a discreteness of 1—5 m, which can be done only in open-hole wells, are required to collect more precise information on the hydrogeological properties of the massif.

Prior to these studies, it seems advisable to drill out boreholes accounting for a larger diameter to prevent the clogging of the borehole walls and cracks resulting from the application of additives in drilling fluids during exploration drilling, as well as long downtime of wells. One should refuse the application of drilling fluids when drilling/widening wellbores [8, 10], which contribute to additional colmatage of the near-wellbore zones, whereas the wellbore shall be flushed with clean water only.

Video logging of the wells performed in 2019—2020 showed that the obstruction of the boreholes was caused by collapses in the highly fractured zones of the rocks at the intervals mainly starting from the wellhead to a depth of 250 m and in some cases due to restrictions found it the wellbore. Well surveys revealed neither significant falls nor changes in the geometry of the wellbores at the interval of 250—700 m. Borehole cleanout operations have demonstrated that rock plugs in the wellbore are easily penetrable by a drilling tool. At the same time, the reoccurrence of rock falls from the uncased borehole walls could not be exclude for the exogenous fracturing interval of the massif. To avoid this, the collapsible sections of the wellbores were recommended to be overlapped with a casing of a corresponding diameter. Thus, the recommended well design solution suggested that the metal string should not be fitted along the entire depth of the wells: casing should be provided only for the areas of rocks prone to collapse (Figure 5)

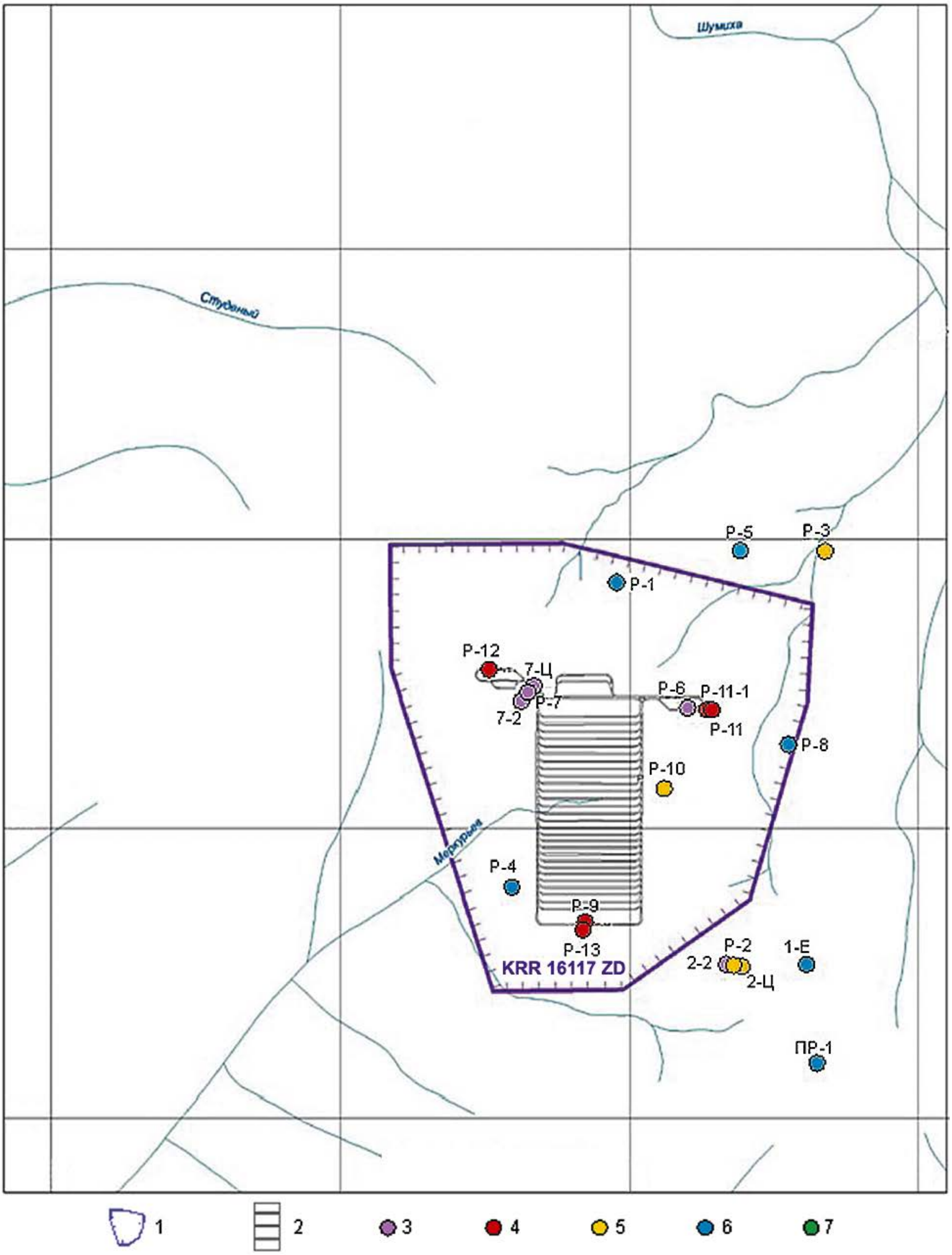

Figure 1. Layout of the wells and priority plans for the abandonment and temporary shut-down:
1 – boundaries of the subsoil plot according to the license for the subsoil use KRR 16117 ZD
2 – boundaries of the URL and DDF RW at horizons +5 and −70 m according to the designs
3 – wells to be abandoned (JSC Eleron)
4 – wells abandoned during the sinking of mine shafts (GDV-301743-TD)
5 – wells planned for temporary shutdown (according to design specifications and estimates GDV-301743-TD)
6 – wells for which the temporary shutdown operations were performed by JSC Krasnoyarskgeologiya in 2020
7 – earlier abandoned wells

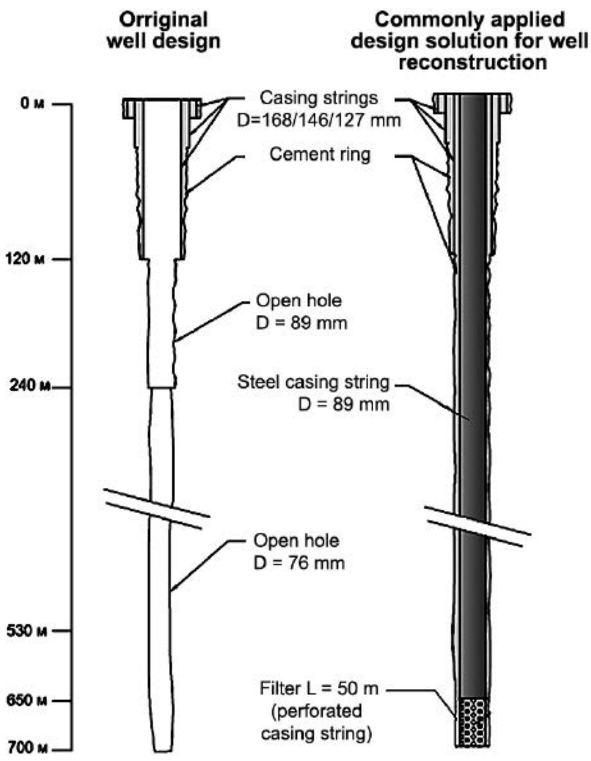

Figure 2. Snapshot of a commonly applied design solution for well reconstruction

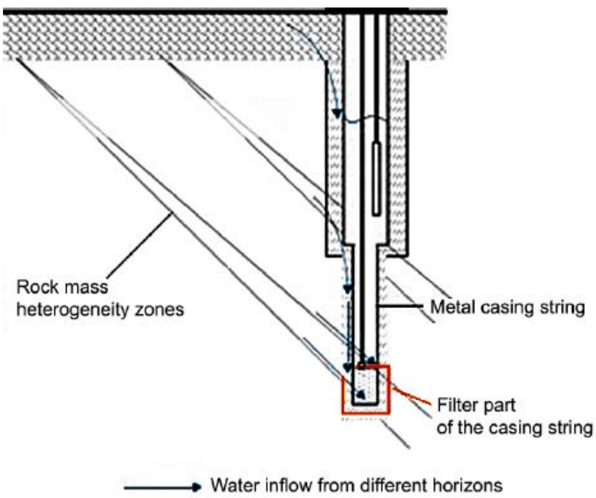

Figure 3. Potential groundwater inflows into the filter zone

and requiring some shuttering — from the wellhead to the depth of 200—250 m. At the below depths it was decided to leave the wellbore open, which could be of practical importance for the development and implementation of further research.

Figure 5 shows the recommended well design seeking to improve the quality and information content of subsequent research, to reduce the total cost of the entire R&D project, to introduce the interval monitoring approach suggesting the use of modern geological exploration methods at the Yeniseiskiy site, including the application of packer systems (Figure 6).

Of particular importance should be also the development of engineering solutions allowing for further abandonment of excavated and planned wells in the Yeniseiskiy area. In addition to already considered wells that were completed at the prospecting and appraisal stages of the project, additional wells are planned to be drilled at the next stage of the geological research (exploration stage). The geological exploration designs developed for this stage provide for well drilling both from the surface (Figure 7) and from the underground excavations during the development of the URL underground facilities [10].

Preliminary estimates show that mapping and parametric wells pose a lesser threat to the safety of potential RW disposal. Mapping wells do not penetrate the target disposal horizon and reach a maximum depth of 150 m.

Exploration wells with a depth of up to 700 m drilled from the surface, despite of being located outside the actual RW disposal zone, require more attention during well abandonment due to potential hydraulic connection that can be established between the target horizon and areas of active water exchange by their shafts. In terms of long-term RW disposal safety, the most critical seems to be the issue of abandoning deep exploration wells drilled from the underground excavations. Due to the specific nature of the facility being developed in the Nizhnekanskiy massif, the development of a well abandonment method requires a very specific approach both in terms of the materials and the engineering solutions applied. Not only the regulatory requirements establishing the procedure and specifying the engineering solutions for well abandonment should be met [9], but the essential goal of restoring the natural flow of groundwater in the well area should be addressed by these measures. A set of requirements specified by POSIVA for the abandoned wells can be considered adequate as regards the accounting of all possible factors contributing to radionuclide migration beyond the boundaries of the future disposal system:

- insulating properties of materials should be preserved during the entire period while the waste potentially remains hazardous;
- along the wellbore no filtration flows should occur between horizons;
- the possibility of inadvertent intrusion into the wellbore should be excluded;
- in the short and super long terms, the efficiency of methods and materials should not be affected by seasonal, climatic and other variable factors of natural origin;

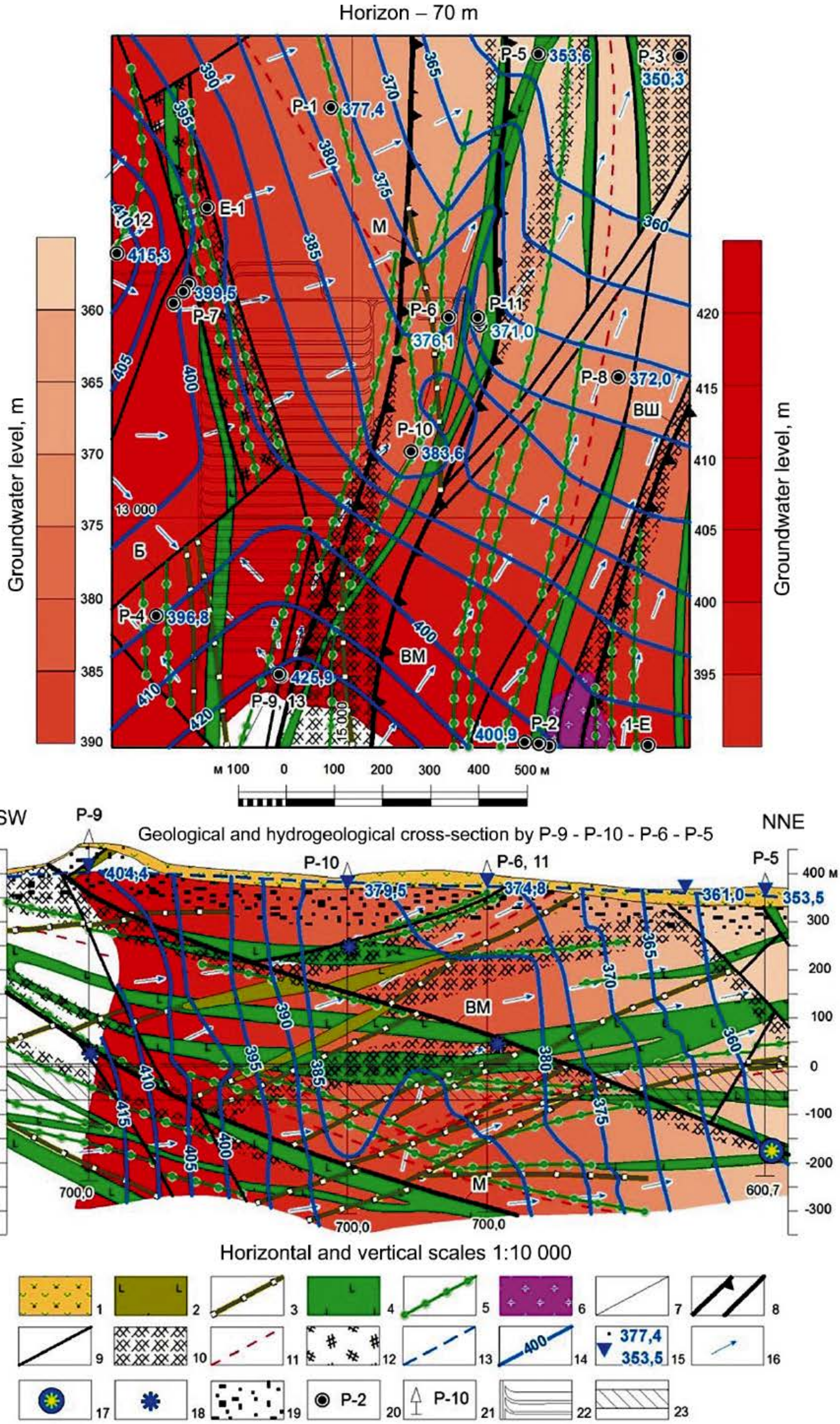

Figure 4. Features of hydrogeological conditions based on the studies performed at the Yeniseiskiy site

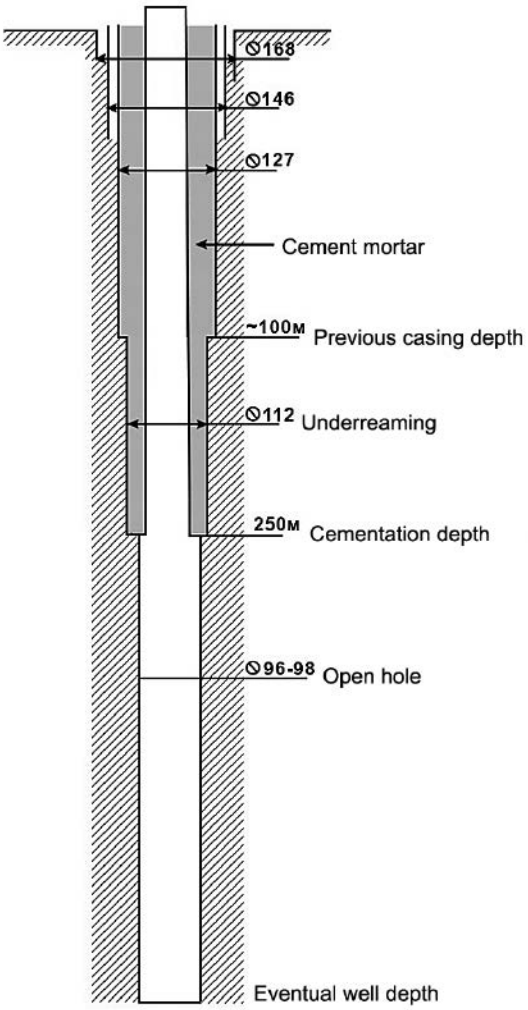

Figure 5. Well cementation at the Yeniseiskiy area

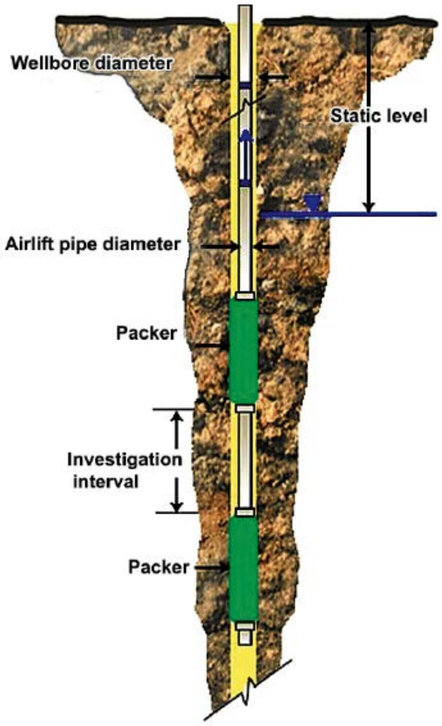

Figure 6. Option considered to arrange a two-packer system in an open section of a wellbore for interval monitoring purposes

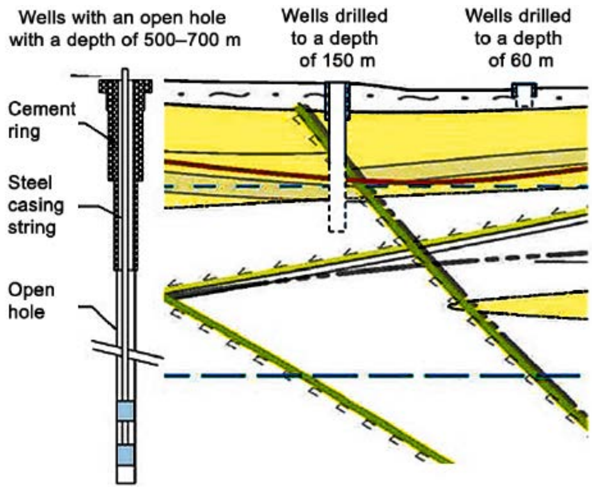

Figure 7. Examples of well designs planned for surface drilling in the Yeniseiskiy area

- permeability of materials applied should be low enough to restore natural groundwater flows.

Requirements for the selection and functional properties of plugging materials used for well abandonment purposes can be summarized as follows [11]:

- performance: automation of the plugging process with the material supplied in the desired form with certain strength characteristics (after hardening) and capable of ensuring the structural unity of the filling material with the host rocks;
- adaptability of materials: the material should not induce the degradation of wellbore and should have adequate plasticity characteristics;
- hydraulic permeability should be as low as possible and at least no more than the permeability of the surrounding rock;
- long-term stability: chemical composition of the material should remain constant over time and the material itself should not react with the surrounding rock, should be mechanically resistant to the degradation caused by natural factors, such as groundwater flow, should remain thermally stable in the expected range of ambient temperatures;
- swelling: material properties should provide maximum filling of the voids between the plugging material and the walls of the wellbore to prevent the occurrence of areas with a higher permeability than the average one.

Table 1 presents a comparative analysis of plugging materials considered as potentially suitable for well abandonment purposes.

Comparison of material properties presented in Table 1 and the results of studies at international analogue facilities [12] demonstrate that due to the unique properties of bentonite clays, bentonite and bentonite-based materials should be considered as the preferred ones for well abandonment purposes.

Table 1. Comparison of plugging material properties

Material	Advantages	Disadvantages
Barite $BaSO_4$	Chemically inert. Its density increases whereas the permeability decreases over time	Can only be used in vertical or subvertical wells. Minimum achievable permeability in the range of 10^{-10}–10^{-9} m/s
Bentonite	Attainable permeability in the range of 10^{-13}–10^{-11} m/s. Variety of available chemical and physical forms. Long-term stability in a proper environment. High ductility	Low strength. Relatively high cost. Erosion is possible. Long term stability depends on chemical conditions.
Mixture involving 10 % of bentonite and 90 % of sand	High mechanical strength. Low cost	Low strength. Minimum attainable permeability of 10^{-9} m/s. Separation of components can potentially occur during well filling
Blend of 80 % bentonite with 20 % of sand	Attainable permeability in the range of 10^{-11}–10^{-10} m/s. Low cost	Low strength (no bond between sand grains). It's hard to provide disposal at a big depth due to component separation
Cement	Availability. Low cost. High initial strength	It's hard to fill up horizontal wells. Low long-term stability. Shrinkage and cracking. Low plasticity

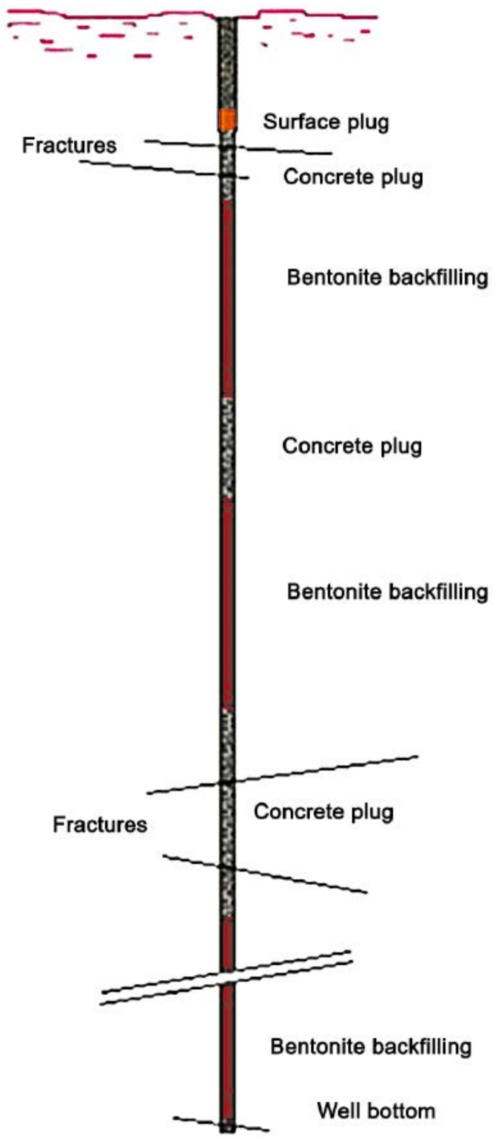

Figure 8. Schematic representation of the multi-layer plugging concept

At the same time, due to insufficient strength properties of bentonite, multilayer plugging is required providing for various combinations of layers involving bentonite and more durable materials (Figure 8). Optimal choice of multilayer plugging materials suggests that the wellbore is divided into excavation disturbed zones of rocks (main zones) to be filled with bentonite material and conditionally monolithic zones with undisturbed rocks, which will be filled with materials that can only provide the mechanical strength of the backfill layers (for example, concrete) and prevent the backfill material from sinking in the main zones of the well. Zone intervals are chosen based on the analysis of the primary geological documentation, as well as video well logging results.

Regardless of the quality and material combinations (Table 1), pre-plugging and plugging operations in the wells should cause no excessive damage to the wellbore walls. Methods commonly applied in the oil and gas industry can be used as a basis for

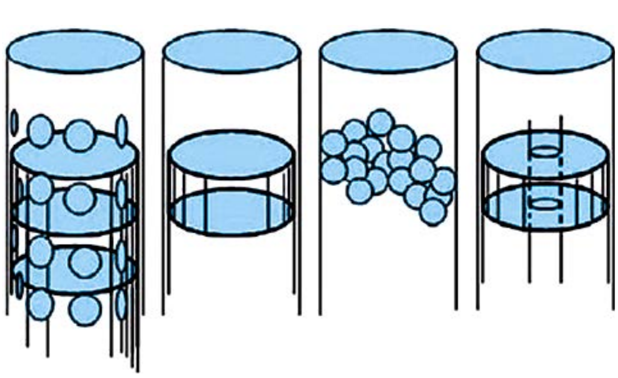

Figure 9. Advanced well abandonment technologies. From left to right: perforated tube, container method, pellets, stacking blocks

the development of proper engineering solutions providing the restoration of the wellbore section and plugging material installation. Figure 9 presents four engineering solutions being considered as potentially suitable for this application [11,12].

1. Perforated tube. The well is backfilled with compacted swellable bentonite blocks enclosed in perforated metal tubes that remain in the wellbore after the abandonment providing the required mechanical strength of the structure. Due to its chemical properties and plasticity, copper pipe was chosen under well abandonment projects implemented by SKB and POSIVA. However, based on field studies, other materials can be also applied for these purposes.

2. Container. To prevent bentonite erosion upon its contact with water in the wellbore during its delivery to the target interval, bentonite blocks are packed into containers and in this form lowered into the wellbore. Blocks squeezed out of containers by a piston, quickly swell and densely fill the corresponding well sections. Depending on the shape and curves of the wellbore, the size of the blocks and containers can differ.

3. Pellets. Borehole sections not being in contact with increased fracturing zones are backfilled with bentonite pellets. Experiments on the application of this method were carried out by NAGRA (Switzerland). This method is believed as a quite feasible option when it comes to the abandonment of shallow wells (up to several tens of meters), for example, the mapping wells. This method does not provide the plugging density required to achieve the desired rock mass permeability.

4. Stacking blocks. Cylindrical blocks of compacted swellable material are lowered into the well. These blocks are strung on a copper rod, which remains in the wellbore. The method provides a high filling density of the well section. However, lowering of the blocks into a well filled with water can result in a rapid erosion.

Table 2 provides a comparison of the above well plugging methods.

Preliminary estimates show that perforated tube and container methods can be considered as most promising options for the abandonment of wells at the Yeniseiskiy site. The perforated tube method is relatively simple both in terms of backfill cassette fabrication and its delivery to the wellbore on drill pipes or with a logging winch. At the same time, high metal consumption is still viewed as an important disadvantage of this method. Container method is significantly complicated by the need for additional development of a set of shipping containers. The method to be considered as the most adequate one in terms of the insulating properties provided by the material, its delivery and the delivery means applied should be selected based on comprehensive laboratory and field studies. To compare the available options and to develop new well abandonment methods for the Yeniseiskiy site, a Comprehensive Research Program … provides for the implementation of relevant R&D primarily focused on the selection of bentonite-based plugging material. Development of appropriate well abandonment methods is stated as a priority area of URL research suggesting that the effectiveness of the proposed solutions should be verified at various R&D stages: from laboratory studies to full-scale tests implemented using purpose-developed units in URL excavations.

Conclusion

Since the studies aiming to provide more precise information on hydrogeological and hydrogeochemical setup at the Yeniseiskiy site, including the one corresponding to the target depth interval, should be continued, it's believed quite feasible that already available wells are to be applied for these purposes as well.

Methods commonly used to fit the wells with all necessary equipment for the hydrogeological research were analyzed showing that they do not fully take into account the specific features of the facility being established at the Yeniseiskiy site and are

Table 2. Comparison of plugging material installation methods

Method	Advantages	Disadvantages	Well length
Perforated tube	Tested in practice, high density	Significant metal consumption, preliminary well drainage is required	Up to 1,000 m
Container	High density, not prone to erosion	Lack of experience in practical application, low performance	Unlimited
Pellets	Tested in oil and gas industry	Erosion, low density, heterogeneity	Up to 50 m
Stacking blocks	High density	Risk of erosion at great depths, preliminary well drainage is required	Up to 100 m

focused on fundamentally different geological and hydrogeological features of the rock mass. This will negatively affect both the obtained research results and create additional risks at the subsequent stages of the DDF RW life cycle.

The paper provides some proposals on most preferred well design options addressing the research goals according to the main research areas indicated, as well as those associated with long-term monitoring. Thus, the idea of fitting the wells with a metal string running along the entire well depth was renounced, whereas casing was proposed to be applied only for the rock areas considered as prone to collapsing and requiring some shuttering - up to an elevation of 200-250 m. It was recommended to leave the wellbore open at depths below those indicated above, which will be of practical importance for further development and implementation of the R&D program.

Requirements on the well abandonment operations were evaluated considering the tasks set for the DDF RW development which allowed to select appropriate plugging methods for well abandonment that could be considered as potentially suitable for the case study of the Nizhnekanskiy rock mass. The final decision regarding most suitable method both in terms of the insulating material properties and the method of its delivery and the technical means applied will be made based on a complex of laboratory and field studies provided for under the Comprehensive Research Program for the Demonstration of the Long-Term RW Disposal Safety and Optimization of Operational Parameters.

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Bibiliographic description

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