UNDERGROUND RESEARCH LABORATORY IN THE NIZHNEKANSKIY MASSIF: EVOLUTIONARY DESIGN STUDY

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The role of underground research laboratories (hereinafter URL) is recognized globally and involves the following points: URL enables research and demonstration aimed at evaluating the feasibility of technological processes under actual spatial scales and geological setup. In recent years, quite a lot of articles and reviews was published [1–5], concerning the issues associated with URLs established to demonstrate the safety of radioactive waste deep geological disposal. It should be noted that 25 URLs were developed globally for various purposes. Most similar to the Russian one by their purpose are those being site-specific (located at potential disposal sites) and excavated in crystalline bedrock (granite and gneiss), namely: operating URL ONKALO (Finland) and the one planned for construction in 2020 in China (Beishan Province). Among all the publications there are several articles [6–14] focused on particular studies planned to be carried out in the Russian URL being under construction at the site of Nizhnekanskiy massif in the vicinity of Zheleznogorsk city (Krasnoyarsk region). This paper presents the designs of the Russian URL being for the first time ever discussed in a holistic and dynamic manner starting with the construction stage and up to the closure of the disposal facility.

Keywords: radioactive waste, safety assessment, underground research laboratory, research program at construction stage, long-term experiments, massif characterization, complex of in situ studies of rock mass state, URL construction.

Best international practices and national engineering solutions for URL layout development were constantly evaluated by main scientific communities being concerned with the URL topic. These were discussed under the auspices of the IAEA and NEA OECD with an active engagement of experts from FSUE NO RAO and IBRAE RAS [15,16].

The layout of main excavations constituting to the established URL (Figure 1) was set forth under the repository development strategy [17] and the comprehensive R&D program [18] originally

developed by FSUE NO RAO and the St. Petersburg branch of the Federal Center for Scientific and Technical Research Eleron (VNIPIET). This layout is considered as a baseline for the currently developed URL designs.

URL layout evolved based on some particular tasks to be addressed by the purpose-developed URL, including:

- characterization of the rock mass (a detailed study of its geological structure, mechanical, hydrogeological and geochemical conditions), including

Figure 1. General layout of the URL

the identification of fracture zones and the study of their water-conducting properties that will enable the final statement on the suitability of the site for deep disposal facility construction;

- full-scale experiments to study the behavior of engineered barrier materials and structures under conditions being considered to the extent possible similar to the actual disposal ones taking into account all impacting factors, including pressure and heat loads, geochemical and biochemical features of the rock mass and groundwater, changes in the rock mass state due to construction and mining activities;
- demonstrating the soundness of the performed repository safety assessments to regulatory

authorities and the general public, validation of parameters and models used in the design estimates;

- refinement of process flow charts to be implemented during repository operation: arrangements that should be put in place in the excavations prior to RW emplacement, RW transportation and backfilling.

Current mipmapping level provides for 14 work packages with relevant work scope and methods engaged described for most of them (Figure 2). A most precise description is provided for work packages 1.1–1.5 and 2.1–2.6. The general approach to the development of the resulting concept can be described as follows: what and why should be investigated, including references to relevant regulatory requirements and sections of the long-term safety case; what types of equipment and measuring tools will be required; what infrastructure facilities are needed (power supply, communications, etc.), what is the time input, etc. Below are considered some examples of currently perceived work packages.

All mining operations should be accompanied by work packages 1.1 (regular survey at the face) and 1.2 (interval survey at the face): both during shaft sinking and horizontal borehole excavation at the target depth. The studies indicated as “Regular survey” are provided for by relevant provisions of mining regulations [19]. Regular surveys should be carried out in each cycle of a mining operation involving the following activities: geological logging of rock outcrops (description of rocks, mapping of fractures, rock sampling and conservation of rock samples, including samples of fault filler material) and hydrogeological observations (assessment and

Figure 2. Main work packages within the URL lifecycle

identification of water inflows in discontinuous fault zones, groundwater sampling and conservation of groundwater samples). In contrast to mining standards, these activities are distinguished by a greater frequency and degree of detail. Interval investigations are planned to be carried out with a much lower frequency – up to 15 investigations in each shaft and up to 40 – in horizontal excavations.

In addition to regular surveys the following investigations are planned during interval surveys (1.2) at the face and on the walls, roof and footing of excavations (shafts and horizons):

- short boreholes will be drilled as part of geological research with rock samples being collected for petrographic studies to identify physical and mechanical properties of the bedrock;
- monitoring stations will be set up as part of hydrogeological research activities.

Geomechanical and geophysical investigations are planned to be performed in the URL as well.

Data from the wells drilled from the points corresponding to future URL shafts helps identifying “characteristic zones” for the interval studies that are to be performed during shaft sinking (Table 1). Characteristic zones of horizontal excavations were identified by combining the available 3D-model of the rock mass with the URL model (Figure 3).

Table 1. Interval survey zones along the ventilation shaft

Depth, m	Type of research*
42–52	ABC
100–105	ACD
208–210	ABC
250–320	ACD
355–360	ABC
400–405	ABC
440–445	ABC
470–490	ABC

*A. Geological research:

- large-scale fracture measurements, description of fracture morphology and its mineral filling;
- drilling of short boreholes with samples taken for petrographic research to identify physical and mechanical properties of rocks.

B. Hydrogeological studies with monitoring stations being fitted for:

- water inflow evaluations;
- groundwater sampling and sample conservation;
- setting up monitoring stations.

C. Geomechanical studies:

- measurement of currently available stresses within the rock mass and identification of their propagation.

D. Geophysical surveys:

- evaluation of the excavation damaged zone (EDZ) in the vicinity of the excavations;
- selection of “less impacting” excavation methods;
- evaluation of structural disturbances within the rock mass to identify their propagation direction and orientation.

Figure 3. Areas with URL excavations being intersected by discontinuous fault zones within the rock mass were identified by combining the rock mass 3D-models with the URL model: a) crushing zone intersected by transport-mining excavation; b) transport and production excavation intersecting a fractured/faulted area within the rock mass; c) intersection of a disposal gallery by a fractured/faulted area within the rock mass; d) area with the ventilation shaft being intersected by a fault/large fracture.

So far, the set of main tools to be applied during regular and interval surveys have been generally specified [6].

According to work package 1.3, a number of experimental units will be fitted within the shafts: these will be installed in the pump chambers provided for in the designs.

To arrange these units the following work flow sequence should be performed:

- wells will be drilled towards structural disturbance zones available within the rock mass with rock samples being collected for research purposes;
- a complex of geophysical studies will be performed in the wells to identify the properties of rocks in the rock mass sections being located far away from the excavations;
- video logging of boreholes, identification of rock bedding elements;
- hydrogeological studies;
- arrangement of monitoring stations.

In addition to the valuable data on the rock mass sections being adjacent to the disposal zone, long-term monitoring will provide the basis allowing to confirm or adjust the design parameters based on the integrated characteristics of the hydrodynamic mode within the disposal zone during URL operation, i. e. the overall balance of groundwater inflow

and volumes of the water pumped from underground structures.

The monitoring work package (1.4) should enable long-term evaluation of data obtained by the observation system fitted within the underground excavations and at the surface. This package will involve: hydrogeological (water flow in the excavations) and hydrogeochemical measurements; geotechnical measurements (strain-stress state analysis, deformation); radiation monitoring of naturally occurring radionuclides in the underground excavations; seismic and acoustic monitoring (control over discontinuous faults); thermometric measurements, hydrogeological, hydro-chemical, hydrological, seismological and geodynamic monitoring data, as well as parameters of the actual radiation environment. Proposals regarding particular monitoring systems have been published already [7–11].

Obviously, research performed under work packages 1.1–1.4 should be arranged in a way allowing

to reflect all the data obtained via the developed geological model [20]. Work package 1.5 being focused on the selection of suitable locations for the research facilities inside URL excavations is considered as the primary one enabling actual application of the obtained data. It should be noted that the research facilities are required to be located outside the selected single area within the underground URL complex since different groups of experiments impose different requirements on the characteristics of the rock mass and excavations where these experiments are actually implemented (Table 2).

A set of studies performed during URL excavation (regular and interval surveys) is considered as the only opportunity enabling to determine the exact location of the research facilities. The information obtained allows updating the geological model of the rock mass, and, if the required parameters of the studied area are confirmed, it will be ultimately selected as the one intended for the experimental

Table 2. Basic requirements to the excavations incorporating experimental facilities

Types of research during URL operation	Planned R&Ds
Excavations in the vicinity of a discontinuous fault	
Geomechanical experiments	Identification of stresses and their propagation in the rock mass using a set of methods
Hydrogeological experiments	<ul style="list-style-type: none"> • tracer experiments in nearby boreholes; • R&Ds on the water saturation of excavations; • aquifer testing in the boreholes
Microbiological and geochemical experiments	<ul style="list-style-type: none"> • migration of radionuclides in fracture waters; • effect of microbiological processes on the corrosion of metal EBS
Experiments addressing the properties of EBS materials	<ul style="list-style-type: none"> • simulated behavior of EBS materials under repository conditions; • simulated radionuclide migration in fracture groundwater
Excavation intersects discontinuous fault zones	
Hydrogeological experiments	<ul style="list-style-type: none"> • tracer experiments in nearby boreholes; • R&Ds on water saturation of excavations; • aquifer testing in the boreholes
Excavations located within fractured rocks	
Thermomechanical experiments	<ul style="list-style-type: none"> • impact of thermal and force stress on the rocks; • impact of heat output on loosened rock zone
Hydrogeological experiments	<ul style="list-style-type: none"> • tracer experiments in nearby boreholes; • R&Ds on water saturation of excavations; • aquifer testing in the boreholes
Microbiological and geochemical experiments	<ul style="list-style-type: none"> • migration of radionuclides in fracture waters; • effects of microbiological processes on the corrosion of metal EBS; • chemically-induced and biogenic gas formation
Experiments addressing the properties of EBS materials	<ul style="list-style-type: none"> • colloid formation and erosion rate of EBS structure materials; • gas transport processes in EBS structure materials; • impacts produced by temperature and pore water on EBS material evolution
Excavations in monolithic rocks	
Thermomechanical experiments	Integrated experiment
Hydrogeological experiments	<ul style="list-style-type: none"> • tracer experiments in nearby boreholes; • R&Ds on the saturation of the excavations; • aquifer testing in the boreholes
Geomechanical experiments	Identification of stresses and their propagation in the rock mass based on a set of methods

facility installation. To date, the areas with the excavations being intersected by discontinuous faults were identified by combining the available 3D-model of the rock mass with the URL one (Figure 3), including some research facilities that are planned to be constructed in these areas. It should be noted one more time that this information could be confirmed or rejected only based on the surveys of rock excavations performed during their construction.

7 main groups of experiments are planned to be implemented in the URL, namely: thermomechanical (2.1), geomechanical (2.2), hydrogeological (2.3), on the evaluation of safety barrier material properties (2.4), microbiological and geochemical (2.5), monitoring (2.6), testing of waste emplacement technologies and long-term experiments on the selection of construction materials to be applied at the final stage of repository operation — closure/abandonment of all excavations (2.7).

To date, the experiments identified under work packages 2.1—2.5 have been basically elaborated.

Group 2.1 provides for some research involving the use of purpose-designed facilities to evaluate the effects of thermal and power loads on the loosened area within the rock mass, vaults and walls of the excavations [21]. The experiments were planned using the data on the URLs developed abroad [22—24].

A facility proposed under the work package 2.1 is designed for an integral experiment scheduled at the latest stages of URL operation. It should provide data enabling to evaluate the changes in the main parameters of the rock mass associated with the excavation of disposal boreholes, waste emplacement and following the heating-up of rocks by a heat-emitting mockup waste package and further cooling under natural conditions. Figure 4 presents the basic experimental setup: 2 disposal boreholes intended for mockup RW package emplacement, 8 observation wells (4 observation wells for each borehole being located at different distances from them) for ultrasound studies, video logging and equipment for single measurements; control well for single verification measurements, 8 wells equipped with stationary sensors to track changes in the rock mass target parameters. Due to the application of seismic-acoustic and ultrasonic methods, the experiment will be carried out after the mining operations are completed. The experiment will engage continuous computation support. Available calculation model (Figure 4) will be developed based on the incoming data on the thermal conductivity and other characteristics of the studied rock mass section.

Work package 2.2. provides for the experiments aimed at identifying maximum stresses

causing rock failure, monitoring and predicting the stresses at the stage of facility excavation and operation. Some of them have already been discussed in [14].

Let's consider the simplest and nevertheless interesting experiment aimed at investigating the saturation of underground excavations from the work package 2.3 (Figure 5). To arrange for such an experiment, sections of the underground excavations with naturally-induced water inflows located at a distance from the operations causing increased water inflow should be identified. The experiment suggests that absorbent mats are installed along the contour of a rock excavation (shaft, horizontal excavation). The mats are weighted before the experiment and after its completion; thus, water inflow locations and its amounts can be evaluated based on the resulting difference in their weight. Moreover, this work package involves some aquifer testing, including tracer experiments in boreholes and long-term hydrodynamic observations over a network of wells drilled in the walls, roof and bottom of URL excavations.

Work package 2.4 involves some experiments aimed at identifying the effects produced by elevated temperatures and groundwater composition on the evolution of safety barrier's confinement properties, investigating colloid formation and EBS material degradation processes. It also features some experiments focused on the effects produced by gas transfer processes on the quality of bentonite buffer, verifying functional characteristics of RW matrix and clay-based protective barriers in the presence of steel shells based on large-scale mockups under real-life conditions.

Based on international experience, bentonite clays from the deposits of the Russian Federation [25, 26] and its neighboring countries (Kazakhstan, Armenia, Azerbaijan, etc.) are considered as clay materials suitable for safety barrier construction.

The scope of geochemical and microbiological experimental studies (2.5) takes into account [13] existing knowledge on the influence of these processes on the groundwater flows and their localization, including radionuclide migration inside large fracture zones. In addition, some experiments are scheduled to study the effects of geochemical and microbiological processes on EBS materials, including their corrosion and gas generation.

Activities constituting to the work package 2.6 associated with monitoring will be implemented at the stage of URL operation (WP 3.1). Testing of RW emplacement methods and long-term experiments involving materials intended for DDF RW closure (WP 2.7) will be launched later after the design solutions on RW packages and disposal boreholes are

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Figure 4. Experiment involving mockup RW heating

Figure 5. Experiment layout to study the saturation of rock excavations

specified and will continue up to the completion of DDF RW closure operations.

Several important aspects being common for all the above experiments should be noted:

- each of them should provide convincing evidence associated with one or several regulatory requirements on the contents of the DDF RW safety analysis report;
- experiments will be arranged according to the following flow chart:
 - layout based on a theoretical calculation model with available data;
 - a refined layout considering data (observation network, laboratory examination of core, groundwater, etc.) available at the time when the location of an experiment was identified;
 - a refined layout taking into account actual data based on the experiment location;
 - possible adjustment of the calculation model upon alterations in the experimental conditions;
- observations and research will be arranged in a way potentially causing minimum damage to the rock mass.

The latter circumstance is believed to be especially important and it should be emphasized that some remarks already expressed by certain experts being concerned about potential excessive damage to the rock mass integrity come from those who took part in the development of DDF RW's basic layout (two horizons with through boreholes and RW class 2 disposal occupying the basic capacity of the excavations). In contrast to the previously proposed DDF RW concept, options providing for dead-end disposal borehole designs are currently being considered.

As it comes to the rock disturbance not being caused by the construction process, but by the processes implemented to obtain the data demonstrating the long-term safety of the final RW disposal facility, it's worth noting that the assumed damage caused by the R&D program is greatly overestimated. Certainly, the actual scale of the R&D program, including the activities performed during borehole excavation, did contribute to these concerns. The scope of the planned research stems from the lack of data due to the insufficient knowledge on the rock mass. Whereas, a neutral forecast on the rock properties and characteristics being considered as the fundamental ones in terms of RW disposal was accepted as a baseline one. Therefore, to refute this forecast, a maximum possible amount of research is worth to be implemented involving only a few research activities that can cause minor disturbance to the rock mass. As already mentioned in this article, non-destructive/minor impacting research methods are being considered in the first place.

Sufficiency and reliability of the information on rock mass characteristics derived from such methods will determine the feasibility of applying other research methods associated with minor additional disturbances, for example, borehole methods. Under the R&D program, prior to the start of mining operations, minor impacting and borehole methods are presented in approximately equal proportions with the former group being considered as a priority one despite the lower reliability of the results obtained. A case in point is the research planned as part of the scientific support during shaft sinking: regular survey data obtained solely by applying less impacting research methods and entered into the calculation complex immediately after the bottom of the shaft is cleared of the first broken rock mass will be processed. The resulting data will help to get a precise information on the locations from which the short boreholes are to be drilled and to optimize their number in the selected intervals. It's worth reminding that the intervals are selected based on the geological model data compiled from the data of the prospecting and evaluation stages of exploration. In general, according to the scientific community, the volume of research causing disturbances to the rock mass will decrease along with the amount of actual evidence on the rock mass obtained in real time using non-destructive methods. However, complete rejection of destructive research methods used to verify the results of the non-destructive ones, namely, by borehole methods, seems to be quite risky considering the rock mass characterization required for the long-term safety demonstration.

To conclude the above brief summary on the development of the URL layout, the following points should be noted:

1. Proposals on the URL layout were considered at a joint meeting of the STC No. 5 and No. 10 of the State Atomic Energy Corporation Rosatom. Based on the review, it was recommended:

- to submit the proposed list of URL R&D groups to SC Rosatom for approval and to introduce the proposed adjustments into URL designs on a top-priority basis;
- URL operation should provide for thermomechanical, geomechanical, hydrogeological, microbiological, geochemical experiments and research to study the properties of barrier materials; operation of observation network and experimental units fitted within vertical shafts, development of engineering solutions for RW emplacement and backfilling for excavation closure purposes.

2. Detailed proposals on URL layout which are now being prepared for the release will be issued as a separate publication.

3. Without claiming to be exhaustive, these proposals should, nevertheless, serve a basis for further elaboration and development, mainly including those associated with methodological and instrumental support of the experiments.

4. The pool of experts being engaged in the formation and implementation of the URL R&D program tends to get wider. Engagement of experts from the Siberian State University [20] charged with the important task of training future URL personnel is seen as a most valuable contribution in this regard.

Russian URL design development became possible thanks to the engagement of a large number of experts, including:

- The Federal State Unitary Enterprise National Operator for Radioactive Waste Management: Beigul V. P., Konovalov V. Yu., Kirik S. V.;
- St. Petersburg branch of JSC FCNIVT SNPO Eleon — VNIPIET: Demin A. V.;
- IBRAE RAS: Barinov A. S., Bogatov S. A., Krychkov D. V., Moiseenko E. V., Kapyrin I. V., Rastorguev A. V., Neuvazhayev G. D., Boldyrev K. A., Saveleva E. A., Svitelman V. S., Morozov O. A., Tokarchuk A. D., Spynkov V. I.;
- IGM RAS: Petrov V. A., Cochkin B. T., Krupskaya V. V., Platé A. N., Ustinov S. A., Nafigin I. O., Lexin A. B.;
- IPCE RAS: Kulukhin S. A., Ershov B. G., Zakharova E. V., Martynov K. V., Safonov A. V.;
- Lomonosov Moscow State University: Kalmykov S. N., Petrov V. G., Vlasova I. E., Romanchuk A. Yu.;
- NUST MISIS: Gupalo V. S., etc.,
- Geophysical Center of RAS: Morozov V. N., Tatarinov V. N., Maneuevich A. I.;
- Saint-Petersburg Division of the RAS Environmental Geoscience Institute: Rumynin V. G., Nikulenkova A. M., Schwartz A. A.;
- OJSC Krasnoyarskgeologiya: Ozersky A. Yu., Ozersky D. A., Karaulov V. A.;
- OJSC SPb-Giproshakht: Travin A. V., Morin A. A.

Reference

1. Tsebakovskaya N. S. et al. *Obzor zarubezhnykh praktik zahoroneniya OYAT i RAO* [Review of foreign practices for the disposal of spent nuclear fuel and radioactive waste]. Ed. by I. I. Linge, Yu. D. Poljakov. Moscow, Komtehprint Publ., 2015. 208 p.
2. Tsebakovskaya N. S., Utkin S. S., Konovalov V. Yu. Zarubezhnye proekty zahoroneniya OYAT i RAO. Chast' II. Aktual'noe sostoyanie proektov sozdaniya punktov glubinnogo geologicheskogo zahoroneniya v SSHA, Kanade i stranah Aziatskogo regiona. [International Experience in Deep Geological Disposal of SNF and RW. Part II. Current Progress in Deep Geological Disposal of Radioactive Waste and Spent Fuel

in the U.S., Canada and Asian Countries]. *Preprint IBRAE no. IBRAE-2017-04*. Moscow, Nuclear Safety Institute Publ., 2017. 41 p.

3. Tsebakovskaya N. S., Utkin S. S., Pron I. A., Konovalov V. Yu. Zarubezhnye proekty zahoroneniya OYAT i RAO. Chast' III. Zarubezhnyy opyt sozdaniya i ekspluatatsii podzemnykh issledovatel'skikh laboratorij [International Experience in Deep Geological Disposal of SNF and RW. Part 3. International experience in development and operation of underground research laboratories]. *Preprint IBRAE no. IBRAE-2017-02*. Moscow, Nuclear Safety Institute Publ., 2017. 35 p.

4. Tsebakovskaya N. S., Utkin S. S., Linge I. I., Pron I. A. Zarubezhnye proekty zakhoroneniya OYAT i RAO. Chast' 1. Aktual'noe sostoyanie proektov sozdaniya punktov glubinnogo geologicheskogo zakhoroneniya v evropeiskikh stranakh [Foreign SNF and RW disposal projects. Part I. Current status of projects for the creation of deep geological burial sites in European countries]. *Preprint IBRAE no. IBRAE-2017-03*. Moscow, Nuclear Safety Institute Publ., 2017. 35 p.

5. Abalkina I. L., Bolshov L. A., Kapyrin I. V., Linge I. I., Saveleva E. A., Svitelman V. S., Utkin S. S. Obosnovanie dolgovremennoj bezopasnosti zahoroneniya OYAT i RAO na 10 000 i bolee let: metodologiya i sovremennoe sostoyanie [Radioactive Waste and Spent Nuclear Fuel Deep Geological Disposal Long-Term Safety Assessment for 10 000 Years and Over: Methodology and the Current State]. *Preprint IBRAE no. IBRAE-2019-03*. Moscow, Nuclear Safety Institute Publ., 2019. 40 p.

6. Gupalo V. S., Kazakov K. S., Kryuchkov D. V., Pankratenko A. N., Pleshko M. S., Voznesensky A. S., Gaisin R. M., Moseykin V. V. Izuchenie sostoyaniya massiva porod pri stroitel'stve podzemnoj issledovatel'skoj laboratorii kak etap polucheniya iskhodnykh dannykh dlya ocenok bezopasnosti PG-ZRO [The Study of the State of Rock Mass During Construction of Underground Research Laboratory as a Stage of Obtaining Initial Data for the Safety Assessments of Deep Geological Disposal]. *Radioaktivnye otkhody — Radioactive Waste*, 2019, no. 1 (6), pp. 90–99.

7. Tatarinov V. N., Morozov V. N., Kaftan V. I., Manevich A. I., Tatarinova T. A. Podzemnaya issledovatel'skaya laboratoriya: zadachi geodinamicheskikh issledovaniy [Underground Research Laboratory: Problems of Geodynamic Research]. *Radioaktivnye otkhody — Radioactive Waste*, 2019, no. 1 (6), pp. 77–89.

8. Kaftan V. I., Gvishiani A. D., Morozov V. N., Tatarinov V. N. Metodika i rezul'taty opredeleniya dvizhenij i deformacij zemnoj kory po dannym GNSS na geodinamicheskom poligone v rajone zahoroneniya radioaktivnykh othodov [Methods and results of determination of movements and

deformations of the Earth's crust according to GNSS data at the Nizhne-Kansk geodynamic test network in the area of radioactive waste disposal]. *Sovremennye problemy dstantsionnogo zondirovaniya Zemli iz kosmosa — Current problems in remote sensing of the Earth from space*. 2019, vol. 16, no. 1, pp. 83–94. DOI: 10.21046/2070-7401-2019-16-1-83-94.

9. Kamnev E. N., Morozov V. N., Tatarinov V. N., Kaftan V. I. Geodynamics aspects of investigations in underground research laboratory (Nizhnekansk massif). *Eurasian mining*, 2018, no. 2, pp. 11–14. DOI: 10.17580/em.2018.02.03.

10. Tatarinov V., Tatarinova T. Observations by Space Geodesy Methods on Objects of Using Atomic Energy. *IOP Conf. Series: Earth and Environmental Science*. Volume 221. Issue, 2019. DOI: 10.1088/1755-1315/221/1/012065.

11. Tatarinov V. N., Kaftan V. I., Seelev I. N. Study of the Present-Day Geodynamics of the Nizhnekansk Massif for Safe Disposal of Radioactive Wastes. *Atomnaya energiya — Atomic Energy*, 2017, vol. 121, no. 3, pp. 203–207. DOI: 10.1007/s10512-017-0184-5.

12. Kochkin B. T. Zadachi izucheniya geologicheskoy sredy uchastka Enisejskij na tekushchem etape realizatsii proekta zahoroneniya [Investigating the Geological Environment at the Yeniseisky Site: Tasks for the Current Stage of the Disposal Project]. *Radioaktivnye otkhody — Radioactive Waste*, 2019, no. 2 (7), pp. 76–91. DOI: 10.25283/2587-9707-2019-2-76-91.

13. Safonov A. V., Boldyrev K. A. Issledovanie biogennykh processov v PIL PGZRO v Nizhnekanskom massive [URL in the Nizhnekanskiy Massif: Studying Biogenic Processes under HLW Disposal Project]. *Radioaktivnye otkhody — Radioactive Waste*, 2019, no. 2 (7), pp. 92–100. DOI: 10.25283/2587-9707-2019-2-92-100.

14. Tatarinov V. N., Morozov V. N., Manevith A. I., Tatarinova T. A. Podzemnaya issledovatel'skaya laboratoriya: k programme geomekhanicheskikh issledovaniy [Underground Research Laboratory: to the Program of Geomechanical Research]. *Radioaktivnye otkhody — Radioactive Waste*, 2019, no. 2 (7), pp. 101–118. DOI: 10.25283/2587-9707-2019-2-101-118.

15. Saveleva E. A. Mezhdunarodnaya kooperatsiya po geologicheskomu zahoroneniyu RAO v kristallicheskih gornyh porodah (Kristallicheskiy klub) [International Cooperation in Radioactive Waste Disposal in Crystalline Rocks (Crystalline Club)]. *Radioaktivnye otkhody — Radioactive Waste*, 2019, no. 2 (7), pp. 58–64. DOI: 10.25283/2587-9707-2019-2-58-64.

16. Svitelman V. S., Saveleva E. A., Biryukov D. V. Proshedshie nauchno-tekhnicheskie meropriyatiya [Latest events in nuclear science and technologies]. *Radioaktivnye otkhody — Radioactive Waste*, 2018, no. 4 (5), pp. 99–101.

17. Strategiya sozdaniya punkta glubinnogo zahoroneniya radioaktivnykh otkhodov [Strategy for the development of RW deep disposal facility]. *Radioaktivnye otkhody — Radioactive Waste*, 2018, no. 2 (3), pp. 114–120.

18. FGUP “NO RAO”. Kompleksnaya programma issledovaniy v obosnovanie dolgovremennoi bezopasnosti zakhoroneniya RAO i optimizatsii ehkspluatatsionnykh parametrov [National Operator for Radioactive Waste management FSUE. Comprehensive research program in support of long-term safety of radioactive waste disposal and optimization of operational parameters]. 2019.

19. Federal'nye normy i pravila v oblasti promyshlennoi bezopasnosti “Pravila bezopasnosti pri vedenii gornykh rabot i pererabotke tverdykh poleznykh iskopaemykh” [Federal standards and rules of industrial safety “Safety rule at conducting mining operations and processing of solid minerals”]. 2013.

20. Linge I. I., Utkin S. S., Kulagina T. A., Trokhov N. N. Podzemnaya issledovatel'skaya laboratoriya na uchastke “Eniseiskii” Nizhnekanskogo massiva Krasnoyarskogo kraya [Underground research laboratory in “the Yenisei” section of the Nizhnekansky massif of the Krasnoyarsk Region]. *Zhurnal Sibirskogo federal'nogo universiteta. Tekhnika i tekhnologii — Journal of Siberian Federal University. Engineering & Technologies*, 2019, vol. 12, no. 7, pp. 830–841. DOI: 10.17516/1999-494X-0183.

21. Butov R., Drobyshevsky N., Moiseenko E., Tokarev Yu., Konovalov V. Planned coupled thermo-mechanical experiments in Nizhnekansk underground research facility. *DECOVALEX 2019 Symposium on Coupled Processes in Radioactive Waste Disposal and Subsurface Engineering Applications*. November 4–5, 2019, Brugg, Switzerland.

22. J. Christer Andersson. Äspö Pillar Stability Experiment, Final report. Rock mass response to coupled mechanical thermal loading. TR-07-01. Svensk Kärnbränslehantering AB. January 2007. 220 p.

23. Lönnqvist M., Hökmark H. Thermal and thermo-mechanical evolution of the Äspö Prototype Repository rock mass. Modelling and assessment of sensors data undertaken in connection with the dismantling of the outer section. R-13-10. Svensk Kärnbränslehantering AB. January 2015. 179 p.

24. Siren T. ONKALO in Situ Concrete Spalling Experiment — Fracture Mechanics Prediction. Working Report 2013-48. October 2015.

25. Belousov P. E., Krupskaya V. V. Bentonitovye gliny Rossii i stran blizhnego zarubezh'ya [Bentonite clays of Russia and neighboring countries]. *Georesursy — Georesources*, 2019, vol. 21, no. 3, pp. 79–90. DOI: 10.18599/grs.2019.3.79-90.

26. Krupskaya V. V., Zakusin S. V., Dorzhievaa O. V., Chernov M. S., Tyupina E. A. Strukturnye kriterii stabil'nosti montmorillonitov v usloviyakh tekhnogenogo vozdeistviya [Structural criteria for the stability of montmorillonites in man-made conditions].

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Bibliographic description

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