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URL IN THE NIZHNEKANSKIY MASSIF: STUDYING BIOGENIC PROCESSES UNDER HLW DISPOSAL PROJECT

Safonov A. V.[1], Boldyrev K. A.[2]

[1]A. N. Frumkin Institute of Physical Chemistry and Electrochemistry of RAS, Moscow, Russia
[2]Nuclear Safety Institute of RAS, Moscow, Russia

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The article presents a plan of research to study the impact of biogenic processes that are expected to occur under the conditions of the underground research laboratory to be constructed in the Nizhnekanskiy massif of the Krasnoyarsk Krai. It provides an overview of literature sources on the research of biogenic processes conducted in laboratories abroad. The paper focuses on the ways and processes in which the biological processes manifest themselves under the URL conditions within the framework of the high-level waste disposal project implemented in the Nizhnekanskiy massif.

Keywords: *radioactive waste, biogenic processes, indigenous microflora, biocorrosion, underground research laboratory, Nizhnekanskiy massif, geochemistry, safety barriers.*

Modern approach followed by many countries in managing their highly-active radioactive waste (HLW — High Level Waste) implies HLW disposal in deep geological formations. Clay formations are considered by some countries, for example, Belgium and France, as potential bedrock under such projects with crystalline formations being considered as such in the Russian Federation, Canada, Sweden, Finland, Japan and Switzerland. In the Russian Federation, the Yeniseiskiy site (Yenisei Ridge) located in the Nizhnekanskiy gneiss crystalline rock mass (NKM) at a distance of some 6 km from the Zheleznogorsk city (Krasnoyarsk Territory) and 4.5 km from the Yenisei River was selected as the siting area for the deep disposal facility (DRWDF) designed for Class 1 and 2 RW disposal at a depth of some 500 m.

DRWDF is assumed to be a structure involving a system of tunnels and wells designed for the emplacement of RW being subject to pre-disposal treatment. This site has been considered for siting purposes since early 1990s' [1] with some practical efforts being already underway. Design and construction of the repository should obviously account for the international experience gained for over 30-years in URLs all over the world.

As in many similar projects requiring maximum reliability, underground research laboratory (URL) is planned for construction at the initial stage of the project enabling comprehensive analysis and demonstration of the deep disposal safety with fundamentally important and time-consuming R&Ds to be implemented in it under conditions assumed to be similar to the disposal ones.

Demonstration of bedrock suitability for RW disposal purposes ensuring its safety, as well as the feasibility study of the adopted design solutions is seen as the main goal in URL development. A number of studies deemed as important in terms of evaluating the long-term disposal safety of the repository will be carried out in the URL to precise the characteristics of the rock mass and groundwater within the RW disposal area. For this reason, a set of geodynamic, geomechanical, geophysical, geological, hydrogeological, hydrogeochemical, radiometric and microbiological studies are to be carried out under natural and laboratory conditions. Efforts on the latter research area, namely being tuned to relevant studies on the topic of radioactive waste disposal, accelerated in 1980s' and by the 2000s' became an essential part of R&D programs on the development of RW disposal facilities in Sweden, Finland, Switzerland [2—5]. The requirement on super-long storage of waste containing actinides and some long-lived fission products, such as technetium is assumed as the main rationale behind such intensive research on microbiological factors in assessing the disposal safety. Moreover, if during the first hundred years RW components come into contact with engineered barriers designed in keeping with the multi-barrier safety concept, then after their gradual degradation, the contribution of external geochemical processes starts to increase.

This paper aims to set the objectives for the study of biogenic processes in the URL to be constructed under the NKM repository project, as well as to compile a work plan under relevant efforts on the development of a unified model for the long-term safety assessment.

Biogenic processes in the underground environment

According to the contemporary view of the geosphere and its background, microbiological activity is seen as an important mechanism of its transformation over the past 3 billion years. To date, viable microorganisms have been found in samples taken from the depths of up to 5 km at temperatures of up to 120 °C. Under environmental studies, the phenomenon allowing the adaptation of organisms to living under extreme conditions is called extremophilia. High intensity of microbiological activity at considerable depths under extreme conditions is explained by the diversity of metabolic patterns (capability of breathing using various oxidizing agents (electron acceptors): nitrates, ferric iron, sulfates, selenates, arsenates, etc.; the ability to consume electron donors such as ferrous iron, methane, hydrogen, carbon monoxide and other magmatic gases during the breathing process) [6]. Moreover, anaerobic microorganisms possess relatively simple genetic apparatus allowing their speedy adaptation to changing conditions and development of some resistance mechanisms to a wide range of factors (radio-resistance (LD_{100} 5—20 kGy), salt background — up to 300 g/l, temperature 5—120 °C). The ability to build ultrastrong spores and remain in suspended animation for an unlimited time, being activated under favorable conditions, is seen as an important feature of some extremophile microorganisms. Thus, the barrier materials manufactured on the surface and even subjected to chemical and temperature treatment, may contain inactive forms of microorganisms that can be activated under disposal conditions upon the ingress of a wide range of chemical compounds.

In terms of Class 1 RW disposal, thermophilic bacteria are considered as a particularly important ecological group of microorganisms characterized by high growth rates and high levels of metabolic processes [7]. During first hundreds of years after such RW emplacement, these processes can potentially result in significant intensification of safety barriers' degradation as during this time period the near field will be characterized by elevated temperatures due to prolonged heating associated with the radioactive decay of radionuclides contained in the radioactive waste.

Bentonite is considered as most promising materials for the construction of engineered safety barriers (EBS) designed to isolate RW Class 1. The good waterproofing and sorption-precipitation properties of bentonite suggest its use as such, however, it can also contain some significant amounts of organic compounds, iron and nutrients required for bacteriological evolution, as well as a large number of cells and spores of non-indigenous bacteria. Therefore, under bentonite-based EBS concepts, foreign researchers have been constantly paying much attention to steel corrosion under the influence of thermophilic microflora [8, 9]. Moreover, the viability of microorganisms is largely dependent on the bentonite density. Thus, in [10] it was shown that at bentonite density of 1.9 kg/dm^3, microorganisms are present only on material's surface. Also, in [11] it was indicated that the activity of sulfate-reducing bacteria ceases when the density of dry bentonite reaches 1.5 kg/dm^3. In [12], it was pointed out that biological activity is prevented if the bentonite swelling pressure amounts to over 2 MPa. Such pressure corresponds to saturated bentonite density of 1.8 kg/dm^3. Studies carried out by [13] showed that no significant sulfate reduction can be detected in 30/70 sand-bentonite mixture having a dry density of 1.6 kg/dm^3.

To evaluate the role of various biologically induced processes under RW disposal conditions, one should undoubtedly refer to the ample international experience obtained from the study of nuclear legacy storage sites, potential future RW sites and purpose-developed model experiments conducted in underground research laboratories.

Research performed at existing "nuclear legacy" repositories. Aerobic heterotrophic bacteria of various types were identified in the course of microbiological studies of the near field within the high-level waste storage facility in Hanford, USA, contaminated in 1962 with alkalis, nitrates, aluminates, chromates, ^{137}Cs and ^{99}Tc. Gram-positive bacteria were dominated by several species of bacteria, namely: *Arthrobacter, Rhodococcus, and Nocardia* [14], which were able to withstand dose loads of up to 20 kGy, reduce nitrate ions to molecular nitrogen, and radionuclides (U, Tc) and chromate ions — to poorly soluble forms, and oxidize a wide range of organic compounds.

Microbiological studies at the Yucca Mountain repository enabled to identify the following bacteria species: *Bacillus, Arthrobacter, Cellulomonas, Corynebacterium, Pseudomonas, Staphylococcus, Xanthomonas and Flavobacterium.* These species are able to produce organic acids both under aerobic and anaerobic conditions, oxidize Fe(II) and reduce sulfates to sulfides leading to carbon steel corrosion [15].

Research conducted in RW storage facilities at Savannah River National Laboratory (USA) enabled to explore in detail the process of biogenically induced corrosion of aluminum container surfaces in biofilms, primarily resulting from the contact with biogenic sulfide. A high level of bio-fouling was identified on the aluminum surfaces and its growth correlated with pitting intensity on the surface [16].

In the Russian Federation, research was performed to study cement bio-corrosion in the near-surface storage facility of the Federal State Unitary Enterprise "Radon". Thus, bacteria belonging to *Pseudomonas* specie were found to be present in the cement compounds resulting from the solidification of nitrate-containing liquid radioactive waste being able to contribute to the formation of nitrogen, carbon dioxide, acetate, propionate and butyrate ions. It was shown that biogenic processes produce a negative effect on the Portland cement matrix resulting in carbonization and neutralization of cement stone's main minerals leading to the formation of soluble salts, as well as of salts being washed out by water [17].

Geobiological programs for future repositories. The most abundant are the studies associated with potential future repository sites. Relevant OECD NEA program is considered as the most large-scale one of this kind uniting 38 countries [18—21].

Not only the biogeochemical features of potential future repository sites are studied under these investigations, but also the microbiological characteristics of modern barrier materials. Special attention is paid to clay barrier materials being considered as most promising ones under relevant projects.

[22, 23] show that natural clays contain an extremely rich and diverse microbial community. [24] explores the biocorrosion of copper canisters being in contact with a bentonite barrier. The role of sulfate-reducing bacteria leading to copper corrosion due to biogenic sulfide impact was specified. [25, 26] provide an evaluation of changing sorption clay properties under the influence of microbial processes.

Biological experiments conducted globally in URLs. *In situ* URL experiments are viewed as most interesting ones.

A case in point, is a 20-year long experiment in a URL constructed as part of Mont Terri storage facility at a depth of 300 m. The investigations performed therein involved a simulation of processes associated with the generation of hydrogen being considered as an electron donor for microflora. The study performed allowed to define 6 potential processes, in particular: sulfide formation due to lithotrophic sulfate reduction (with hydrogen acting as a reducing agent), heterotrophic sulfate reduction under acetate influence and microbial corrosion of steel. [27] investigated microbiologically driven gas formation, radionuclide transfer with biogenic complexes and the role of biofilms in radionuclide migration..

Table 1 presents a summary of international URL research on microbiological processes.

Areas of experimental research to study the influence of biogenic processes in the NKM URL

Interaction of geological environment with the RW, being subject to disposal in the NKM repository, will certainly take place under conditions suggesting the presence of some microflora, both indigenous and being introduced from the outside. At the same time, it seems quite likely that microbial processes will be intensified due to the temperature effects resulting from the heating of the medium, release of radiolytic gases acting as electron donors under microbial respiration processes (hydrogen, methane, CO, etc.), release of nutrients from matrices: phosphates from glass matrices, iron from steel containers, potassium, sodium and calcium, as well as organic substances from clay materials and the waste containing matrixes.

It should be also noted that bacterial activity can result in the formation of colloidal particles, which may cause colloidal transport of radionuclides.

Table 1. International experience of microbiological studies performed in URLs

Site	Country	Comment	Reference
OLKILUOTO, ONKALO	Finland	Microbiological studies 1997—2010 at a depth of up to 800 m, microbial transformation of iron and changes in the rock sorption capacity.	[28]
Stripa granite mine	Sweden	Microbiological studies, sampling depth 812-820 m and 970-1240 m. Studying the role of the microbial transformation of iron and sulfur in the migration of radionuclides, methane production.	[29]
Asse	Germany	Microbiological research	[30]
Grimsel Test Site	Switzerland	*In situ* experiments, microbial tests to study barrier stability, sulfate reduction, steel corrosion. Full-scale Engineered Barrier EXperiment	[31]
Mont Terri Rock Laboratory	Nagra, Switzerland	20-year field tests, steel corrosion, gas generation, clay degradation	[27]
HADES underground laboratory	Belgium	*In situ* experiments on steel corrosion	[32]
Aspo Hard Rock Laboratory	Oskarshamn, Sweden	Microbe Project 2001. *In situ* experiments. Experiments on steel corrosion, changing clay properties, gas formation and sulfate reduction parameters	[33]

The proposed insulating container (IC) for class 1 radioactive waste is a multi-barrier system, involving the following elements: a can — primary packaging for the vitrified radioactive waste, a shield, canister and a carbon steel container (layers of bentonite and aluminate concrete are installed between the shield and the external wall of the IC) with a thixotropic slip fitted outside of the IC, as well as between the IC wall and the excavation disturbed zone. Biogenic process areas characteristic for this system are shown schematically in Figure 1.

The program for biogenic process research in NKM URL is aimed at providing data on the role of biogenic processes under repository conditions:

- gas generation (methane, carbon dioxide);
- intensification of steel materials' corrosion due to the formation of corrosion-active components (sulfides, acids, complexing agents);
- generation of metabolites forming complex compounds with radionuclides;
- changes in the geochemical environment (changing macro-chemical parameters of water, pH, Eh);
- changes in radionuclide mobility;
- changes in the characteristics of clay-based engineered safety barriers.

Summarizing the above, 9 experimental areas to study the influence of biogenic processes on barriers and radionuclide transfer were proposed to be conducted in the URL:

1. Composition and physiological diversity of the microbial community in the crystalline rock mass area;
2. Corrosion processes in the presence and with the engagement of living microflora under anaerobic conditions;
3. Effects associated with the irradiation of the microflora (experiments with selected samples of microflora and its natural environment under laboratory conditions);
4. Microbiological activity in the barrier material under repository conditions with particular

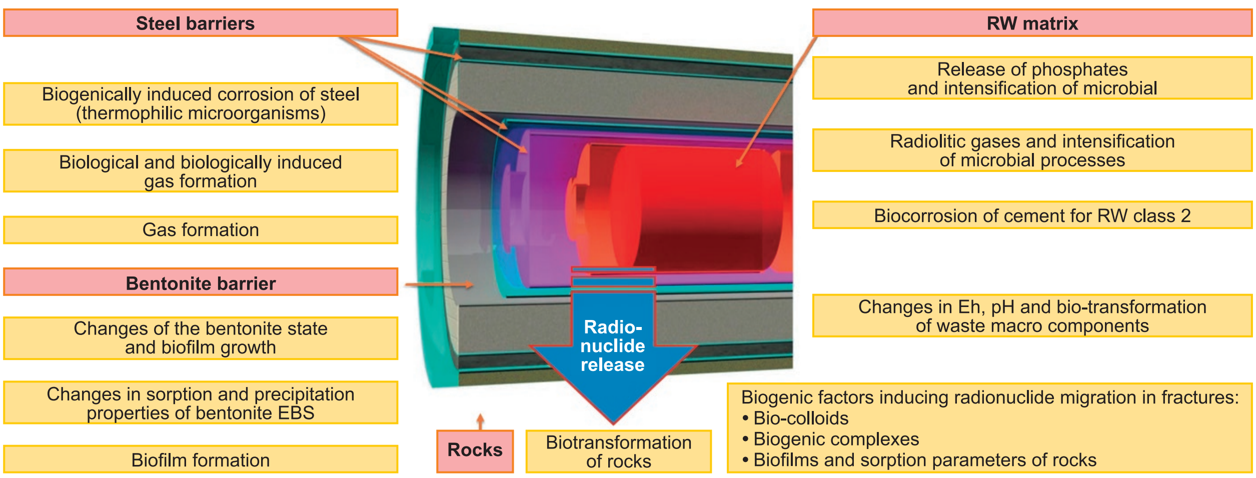

Figure 1. Areas of biogenic processes assumed under super-container design for RW Class 1 disposal in the NKM repository

attention being payed to sulfur-oxidizing and sulfur-reducing, as well as iron-oxidizing and iron-reducing microorganisms;

5. Changes in the sorption and diffusion properties of the rock in case if microbiological films are available;

6. Bio-colloid formation processes;

7. Effect produced on biogenic processes by the leaching of RW class 1 and class 2 matrixes;

8. Evaluating the impact of indigenous microflora on engineered barrier system and radionuclide transfer;

9. Evaluating the effects associated with the introduction of non-indigenous microflora on the functions and properties of engineered barrier system and radionuclide transfer.

The main expected result associated with the planned experiments is to demonstrate the adequacy of EBS materials properties and quality in terms of their ability to withstand the effects of biogenic processes under natural conditions assumed under URL operation. This will allow to simulate scenarios describing the evolution of the multi-barrier safety system of the repository being under development.

The research is focused on the bedrocks and EBS materials: bentonite, materials forming the insulating container, matrix materials used for RW immobilization.

Experiments planned to be conducted in the NKM URL were divided into three main categories:

1. Sampling and identification of local microflora:

- identification of indigenous microflora both in the rock mass and in the crack material;
- study of the structure, properties and impact areas associated with the microbiological community available in the rock mass.

2. Laboratory experiments (conducted in URL units):

- investigation of corrosion processes, including gas generation and oxygen uptake in the presence and with the engagement of living microflora;
- study of the effects associated with the irradiation of the microflora (experiments involving selected samples of microflora and its natural environment under laboratory conditions);
- study of microbiological activity in the barrier material under URL conditions and its impact on bentonite, including the evaluation of hydrogen generation and its impact on biota.

3. In situ field experiments:

- changes in the sorption and diffusion properties of the rock if microbiological films are available;
- study of bio-colloid formation;
- studying the impact produced by the introduction of non-indigenous microflora under the above areas;
- investigating the transfer of microorganisms through EBS material;
- studying the effects produced by leaching products of the sodium aluminum phosphate RW class 1 matrix on biogenic processes;
- studying the effects produced by leaching products of the borosilicate RW class 1 matrix on biogenic processes;
- studying the effects produced by leaching products of the RW class 2 matrix on biogenic processes.

Characteristics/parameters of the measured feature consist in the assessment of the phylogenetic microbiological diversity based on the evaluation of 16S rRNA genes, the number of microorganisms pertaining to various physiological groups, the rates of biogenic processes associated with gas formation, steel corrosion, bentonite corrosion.

To address the objectives of the present study, the following technologies should be applied:

- high-performance DNA sequencing (16S rRNA genes);

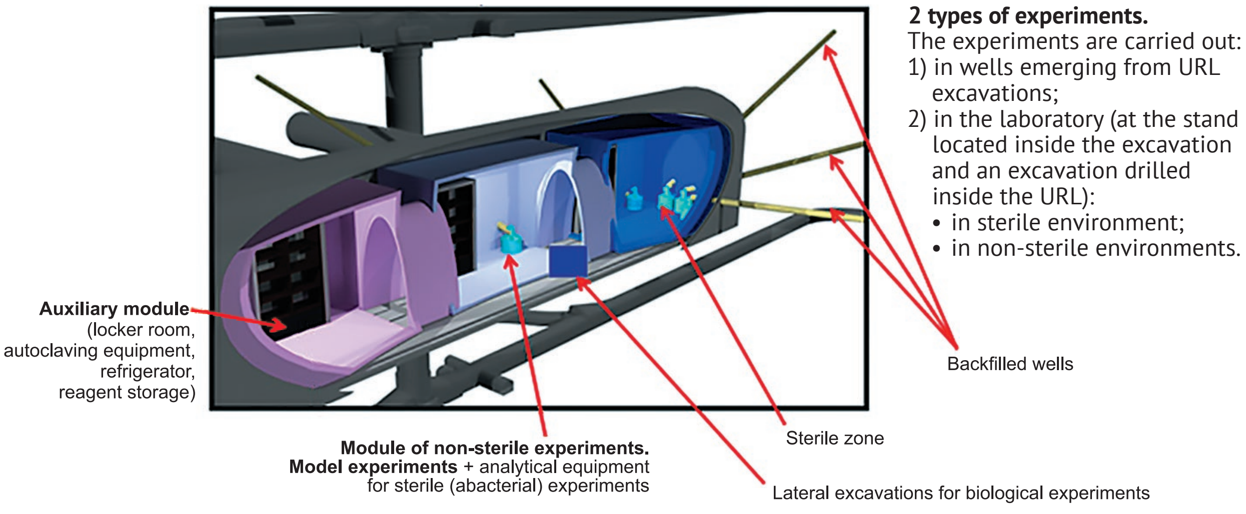

Figure 2. The proposed layout showing experiments under various biological areas to be conducted in the NKM URL

- seeding of natural samples on selective nutrient media to determine microbial abundance;
- laboratory experiments enabling to evaluate the rates of biogenic processes resulting in material degradation and gas formation;
- field experiments enabling to evaluate the rates of biogenic processes resulting in material degradation and gas formation (constantly monitored).

Figure 2 presents the preliminary flow chart allowing to classify URL experiments according to relevant biogenic areas. The excavation should affect the intact zone of the massif in the natural environment and the fracture zone. The investigated area should be located both in fractured rocks and in the undisturbed massif (slightly fractured rocks). Excavations, a full-scale model of a well designed for RW class 1 disposal, as well as relevant excavations for RW class 2 disposal should be used.

The planned studies are closely related to the research projects investigating colloid transfer and radionuclide migration in the near and far field.

Conclusions

The article presents a plan for relevant experimental studies aimed at investigating the influence of biogenic processes that are supposed to be carried out in the URL constructed in the Nizhnekanskiy massif (the Krasnoyarsk Territory). It discusses the ways and processes associated with the biogenic influences assumed to be developed under disposal conditions of the future NKM repository.

Three types of experiments to be conducted in the URL were proposed: sampling and identification of local microflora, laboratory experiments (conducted in URL units) and in situ experiments.

References

1. URL: http://www.norao.ru/about/underground/?fbclid=IwAR2pjBI3S5ow1yAs-rNlEORNZcvAyDTeKt4PPQ-UkzGAjJ1-_NFM4AiW_ogПИЛ (accessed: 05.03.2019).
2. Cooper M. J., Tasker P. W. The Nirex Safety Assessment Research Programme; Annual Report for 1987/88. Nirex Rpt NSS R-102 (1988).
3. West J. M., Hooker P. J., McKinley I. G. *Geochemical Constraints on the Microbial Contaminaion of a Hypothetical UK Deep Geological Repository.* Br. Geological Survey, FLPU 84-8 (1984).
4. European microbiology related to the subsurface disposal of nuclear waste. N Christof, JC Philp — Microbiology of the Deep Subsurface. CRC …, 1997.
5. West J. M., Grogan H. A., McKinley I. G. The Role of Microbiology in the Geological Containment of Radioactive Wastes. https://doi.org/10.1016/B978-0-444-88900-3.50024-2/.
6. Penny S. Amy, Dana L. Halderman. Microbiology of the Terrestrial Deep Subsurface Microbiology of Extreme & Unusual Environments CRC Press, 1997. ISBN 0849383625, 9780849383625.
7. Microbial processes in radioactive waste disposal Pedersen, Karsten Apr 2000; 97 p; ISSN 1404-0344.
8. Necib S. et al. Corrosion of carbon steel in clay environments relevant to radioactive waste geological disposals, *Mont Terri rock laboratory* (Switzerland). Mont Terri Rock Laboratory, 20 Years. Birkhäuser, Cham, 2018. С. 331—344.
9. Smart N. R. et al. The anaerobic corrosion of carbon steel in compacted bentonite exposed to natural Opalinus Clay porewater containing native microbial populations. *Corrosion Engineering, Science and Technology,* 2017, vol. 52, sup1, p. 101—112.
10. Pusch R. Mobility and survival of sulphate-reducing bacteria in compacted and fully water saturated bentonite — microstructural aspects. SKB TR-99-30. Svensk Kärnbränslehantering AB. 1999.
11. Pedersen K. Microbial processes in radioactive waste disposal. SKB TR-00-04. Svensk Kärnbränslehantering AB. 2000.
12. Stroes-Gascoyne S., Hamon C. J., Dixon D. A. The effects of dry density and porewater salinity on the physical and microbiological characteristics of highly compacted bentonite. Ontario Power Generation Report No. 06819-REP-01200-10016-R00. 2006.
13. JNC, H12: Project to establish the scientific and technical basis for HLW disposal in Japan. Supporting Report 2. Repository design and engineering technology. JNC TN1410 2000-003, Japan Nuclear Cycle Development Institute, Tokio, Japan. 2000.
14. Fredrickson J. K., Zachara J. M., Balkwill D. L., et al. Geomicrobiology of high-level nuclear waste-contaminated vadose sediments at the Hanford site, Washington state. *Appl Environ Microbiol.* 2004 Jul; 70 (7):4230-41.
15. Whonchee Lee, Zbigniew Lewandowski , Per H Nielsen & W Allan Hamilton. Role of sulfatereducing bacteria in corrosion of mild steel: A review. *The Journal of Bioadhesion and Biofilm Research,* 1995, vol. 8, iss. 3, p. 165—194. https://doi.org/10.1080/0892701950937827
16. Moreno D. A., Ibars J. R., Ranninger C., De Mele M. F. L., Videla H. A. Evaluation of Stainless Steel Susceptibility to Microbiologically Influenced Corrosion: An Updated Review. In: Llewellyn G. C., Dashek W. V., O'Rear C. E. (eds) Mycotoxins, Wood Decay, Plant Stress, Biocorrosion, and General Biodeterioration. *Biodeterioration Research,* vol 4. Springer, Boston, MA. 1994.
17. Microbiological Aspects of Radioactive Waste Storage. *Radiatsionnaia biologiia, radioecologiia.* 2015. 55 (3) 015, p. 293—301. DOI: 10.7868/S0869803115020125.

18. Report 2016 Äspö Hard Rock Laboratory Annual Report 2016. SKB TR-17-10.
19. The Microbe project Achievements of a 10-year research programme. SKB R-13-49.
20. Edlund J. et al. Microbial Investigations During Infiltration Experiment (INEX) Phase 2. *Posiva Working Report,* 2016, vol. 38, p. 1—39.
21. Olivier X. Leupin, Rizlan Bernier-Latmani, Alexandre Bagnoud, Hugo Moors, Natalie Leys, Katinka Wouters, Simcha Stroes-Gascoyne. Fifteen years of microbiological investigation in Opalinus Clay at the Mont Terri rock laboratory (Switzerland). *Swiss J Geosci* (2017) 110:343–354.
22. Stroes-Gascoyne S., Pedersen K., Haveman S.A., Dekeyser K., Arlinger J., Daumas S., Ekendahl S., Hallbeck L., Hamon C.J., Jahromi N., Delaney T.-L. Occurrence and identification of microorganisms in compacted clay-based buffer material designed for use in a nuclear fuel waste disposal vault. *Can J Microbiol.,* Dec; 43(12):1133-46. (1997).
23. Stroes-Gascoyne S, West J.M. Microbial studies in the Canadian nuclear fuel waste management program. *FEMS Microbiol Rev.* 1997 Jul; 20(3-4):573-90.
24. Pedersen K. Analysis of copper corrosion in compacted bentonite clay as a function of clay density and growth conditions for sulfate-reducing bacteria. *Journal of applied microbiology,* 2010, vol. 108, no. 3, p. 1094—1104.
25. Pedersen K., Motamedi M., Karnland O., Sandén T. Mixing and sulphate-reducing activity of bacteria in swelling, compacted bentonite clay under high-level radioactive waste repository conditions. *J Appl Microbiol,* 2000 Dec; 89(6):1038-47.
26. Clays sorption capacity changes. Microbial Influence on the Performance of Subsurface, Salt-Based Radioactive Waste Repositories. Nuclear Energy Agency (NEA) 46, quai Alphonse Le Gallo 92100 Boulogne-Billancourt, France.
27. Alexandre Bagnoud Karuna Chourey, Robert L., Hettich et al. *Nature Communications,* volume 7, Articlenumber :1 2770 (2016).
28. Pedersen K. Microbial Analytics, Sweden. Title SUMMARY REPORT, MICROBIOLOGY OF OLKILUOTO AND ONKALO GROUNDWATER. ISBN 978-951-652-222-0.
29. Ekendahl S, Arlinger J, Ståhl F, Pedersen K. Characterization of attached bacterial populations in deep granitic groundwater from the Stripa research mine by 16S rRNA gene sequencing and scanning electron microscopy. *Microbiology,* 1994 Jul;140 (Pt 7):1575-83.
30. Zirnstein I, Arnold T, Roeske K. Identification of the Microbial Community in Salt Sumps of the Asse II Pit, a Former Salt Mine Used as a Deep Geological Repository for Intermediate and Low Level Radioactive Waste.
31. Ino K, Konno U, Kouduka M. Deep microbial life in high-quality granitic groundwater from geochemically and geographically distinct underground boreholes. *Environ Microbiol Rep,* 2016 Apr;8(2):285-94. doi: 10.1111/1758-2229.12379.
32. International co-operation and partnerships at the Hades underground research facility (MOL, BELGIUM) A. Sneyers, G. Volckaert, Belgian Nuclear Research Centre SCKCEN Boeretang 200, B-2400 Mol.
33. Äspö Hard Rock Laboratory — Annual Report 2002 (SKB TR-03-10).

Information about the authors

Safonov Aleksej Vladimirovich, PhD, Senior Researcher, A. N. Frumkin Institute of Physical Chemistry and Electrochemistry RAS (31, Leninsky Av., Moscow, 119071, Russia), e-mail: alexeysafonof@gmail.com.
Boldyrev Kirill Aleksandrovich, PhD, Senior Researcher, Nuclear Safety Institute of RAS (52, Bolshaya Tulskaya St., Moscow, 115191, Russia), e-mail: kaboldyrev@ibrae.ac.ru.

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