UDC 504.05, 502.7

Priority parameters of physical processes in a rock mass when determining the safety of radioactive waste disposal

Vladimir S. GUPALO
National University of Science and Technology "MISiS", Moscow, Russia

Consideration of geodynamic, hydrogeochemical, erosion and other quantitative characteristics describing evolutionary processes in a rock mass is carried out when choosing a geological formation for the disposal of radioactive waste. However, the role of various process parameters is not equal for safety ensuring and additional percentages of measurement accuracy are far from always being of fundamental importance. This makes it necessary to identify various types of indicators of the geological environment that determine the safety of radioactive waste disposal for their detailed study in the conditions of the burial site.

An approach is proposed to determine the priority indicators of physical processes in the rock mass that determine the safety of disposal of various types of radioactive waste and require increased attention (accuracy, frequency of measurements) when determining in-situ conditions. To identify such factors, we used the sensitivity analysis method that is a system change in the limits of variable values during security modeling in order to assess their impact on the final result and determine the role of various physical processes in ensuring safety.

It is shown that the safety of isolation depends on various factors when burying "natural", "short-lived", and "long-lived" groups of nuclides. The factors that greatly affect safety when disposing of radioactive waste of these types are highlighted. The list of parameters of the geological environment that characterize the priority mechanisms of localization of various types of radionuclide contamination during burial and requiring the most detailed determination in full-scale conditions is defined.

***Keywords*:** radioactive waste burial; modeling of radionuclide migration; safety assessment; relationship of filtration parameters and rock fracturing; suitability of geological formations; insulating properties of a rock mass

How to cite this article. Gupalo V.S. Priority parameters of physical processes in a rock mass when determining the safety of radioactive waste disposal. Journal of Mining Institute. 2020. Vol. 241. P. 118-124. DOI: 10.31897/PMI.2020.1.118

Introduction. One of the ways of using underground space is the disposal of radioactive waste (RW) in poorly permeable geological formations.

To confirm the suitability of geological sites for long-term isolation of waste containing long-lived radionuclides, underground research laboratories (URL) in crystalline rocks, salts and clays have been created and operated all over the world [13, 17]. The results of research in such URLs are to provide the major dataset necessary for assessing the safety of deep disposal sites for radioactive waste and contributing to demonstrate the reliability of the disposal of radioactive waste in general.

Similar work is carried out in the Russian Federation [1]. As of today, the Russian approaches to safety justification are different from foreign ones on certain issues [4]. In recent decades, a modern concept of safety assessment has been formed in international practice, the key requirement of which is "generating confidence" in the obtained assessments. The concept does not mean the need for a certain number of measuring and calculating procedures, but the mandatory understanding of the processes, influencing factors, the role and mechanisms of natural and engineered barriers, identifying issues that are critical for safety. As a result, first in 2006, and then in 2011, these requirements for developing a safety justification were affirmed by the IAEA standards [3].

Thus, in accordance with modern requirements, a safety justification is a set of arguments and facts that describe, measure and justify the safety of the final isolation facility for RW and the level of confidence in this safety. This means that not only favorable assessment obtained by bona fide execution of the set of measuring and calculating procedures is most important for safety substantiation, but also the evidence of the safety of a facility in the distant future taking into account the impact of possible processes, phenomena and factors of natural and technogenic origin. Such an assessment can only be carried out on the basis of a representative cycle of full-scale studies of the dynamics of properties and the state of engineering and geological elements of an object, which requires consideration when planning research in a URL. At the stage of research planning in an URL, it is important to understand what parameters should be determined, where and by what techniques they should be measured, how to make a quantitative account of the mutual influence of various factors to understand the processes taking place, as well as the role and mechanisms of the barrier system.

The contribution of various parameters to the results of safety assessments is not equal; for some measurement cases, additional percentages of accuracy will not be of fundamental importance and the corresponding costs will not be justified. This determines the need to identify priority indicators of the geological environment that form the safety of disposal of various types of radioactive waste, for their detailed study in the conditions of the isolation object.

The purpose of this work was to develop an approach and determine the list of priority indicators of the geological environment for the disposal of radioactive waste, taking into account their contribution to the results of safety assessments.

Study of the spread of radionuclide contamination from deep disposal sites for radioactive waste. After analyzing the processes occurring during the disposal of radioactive waste, the mechanisms of isolation of radioactive contamination and the corresponding parameters of the geological environment were determined:

- "physical localization" – low volumes of filtered water that limit the amount of nuclide that has passed into the liquid phase due to solubility limits (water exchange parameters, crack opening width, open porosity);
- "geochemical localization" – physical and chemical interaction of contaminants with rock (distribution factor, geometric parameters of the filtration area);
- "deconcentration" – reducing the concentration of contaminants during migration due to the peculiarities of the filtration path and mixing with clean water;
- "delay" – low water movement velocity that ensures the decay of part of radionuclide contaminants on their way out of an area of active water exchange (speed of underground water movement, filtration coefficient, hydraulic gradient, length of the migration path).

Parameters of the specified processes are the basis of the performed safety assessments.

To perform those, it is also necessary to determine the characteristics that describe the evolutionary processes in the rock masses and thus affect the given parameters:

- "tectonics and geodynamics", i.e. changing parameters of pollutant migration paths;
- "hydrogeology", i.e. expected changes in the speeds and volumes of groundwater movement as a result of evolutionary processes;
- "geochemistry", i.e. establishment of ranges of changes in parameters of physical and chemical interaction of pollution and the environment, real parameters of delay of radionuclides.

To highlight factors defining the safety of deep disposal sites for radioactive waste, the method of sensitivity analysis, i.e. the system change beyond the values of variables during the simulation of the security, was used to determine their impact on output indicators. It allows the identification of variables with the greatest impact, as well as to study the model's resistance to data changes. The calculations used a combination of maximum and minimum values of process parameters in rock masses based on the analysis of the results of previously performed studies and ranges of uncertainty in the literature data.

The safety simulation is based on the equation of radionuclide migration in the geological environment, taking sorption into account [5]:

$$n_0 \frac{\partial c}{\partial t} + n_0 \left(\frac{\partial N}{\partial t} = \alpha_s \left(c - \frac{n_0}{\gamma K_d} N \right) \right) = (D_m + \lambda v) \left(\frac{\partial^2 c}{\partial x^2} \right) - v \frac{\partial c}{\partial x}$$

provided

$$N(x,t) \le N_{\max},\ x = r_0 \ldots r_0 + L,\ t = 0..T\ ,$$

$$c\big|_{x=0} = C_0,\ \ c\big|_{x=L} = 0,$$

where n_0 – active fracturing of the geological environment, decimal quantity; c – mass concentration of a component in the liquid phase, kg/m^3; N – conditional concentration of a component in the solid phase, kg/m^3; v – actual Darcy filtration rate, m/year; D_m – molecular diffusion factor, m^2/year; α_s – sorption rate factor, 1/year; γ – bulk rock mass in a fracture zone, kg/m^3; K_d – conditional distribution factor during sorption, m^3/kg; C_0 – concentration of a radionuclide entering into the geological environment (in the liquid phase), kg/m^3; L – conditional maximum length of a migration path (size of the computational domain of the modeling system), m; h – height of modeling area, m;

To solve this system of equations, the AMBER 5.7.1 software was used, on the basis of which a model of substance transfer in a homogeneous medium was implemented.

The role of the examined indicator in ensuring the long-term safety of deep disposal of radioactive waste was defined on the basis of calculations of the size of migration limits of radionuclides of environmentally significant concentrations for the whole period of preservation of relevant isotope potential hazards.

The initial data were used for the simulation:

- characteristics of the most representative radionuclides that are part of high-level radioactive waste generated during the processing of spent nuclear fuel (SNF) (Table);
- the filtration and migration parameters typical for a rock mass with the conditions of slow water exchange. The values were taken based on the results of data generalization from field and laboratory studies, as well as from published works [2, 7, 10, 14, 15].

Characterization of radionuclides

Nuclide	Specific activity, Bq/tU	$T_{1/2}$, year	Volume activity, Bq/m^3	Distribution factor during sorption, m^3/kg	
^{241}Am	7.97E+13	4.32E+02	6.90E+02	1.0E-02	1.0E+01
^{237}Np	1.40E+10	2.14E+06	1.30E+03	1.0E-02	5.0E-01
^{3}H	1.30E+13	1.24E+01	7.60E+06	1.0E-06	1.0E-02
^{14}C	1.42E+10	5.73E+03	2.40E+05	1.0E-04	5.0E-02
^{90}Sr	2.75E+15	2.88E+01	4.90E+03	1.0E-04	1.0
^{137}Cs	3.73E+15	3.00E+01	1.10E+04	2.0E-04	1.0
^{99}Tc	5.99E+11	2.13E+05	2.10E+05	5.0E-04	2.0E-01
^{129}I	1.44E+09	1.57E+07	1.30E+03	1.0E-01	4.0E-01

Indicators of rock parameters for the listed geomechanical, hydrogeological, and geochemical processes were the subject of generalization. The values of the stress-strain state, geodynamic activity from the point of view of crack formation, and the relationship between geomechanical and hydrogeological parameters determined in field and laboratory conditions were analyzed. The behavior of tectonic faults was the most interesting, as they are the most unfavorable areas in terms of permeability and stability of a rock mass. Figure 1 shows a typical tectonic structure of a rock mass represented by a series of different-scale blocks separated by tectonic disturbances of different orders and gives the relationship of deformation processes in the marginal zone of workings (Fig.1, *a*) and the values of crack opening (Fig.1, *b*) with filtration parameters for different fracture zones [2].

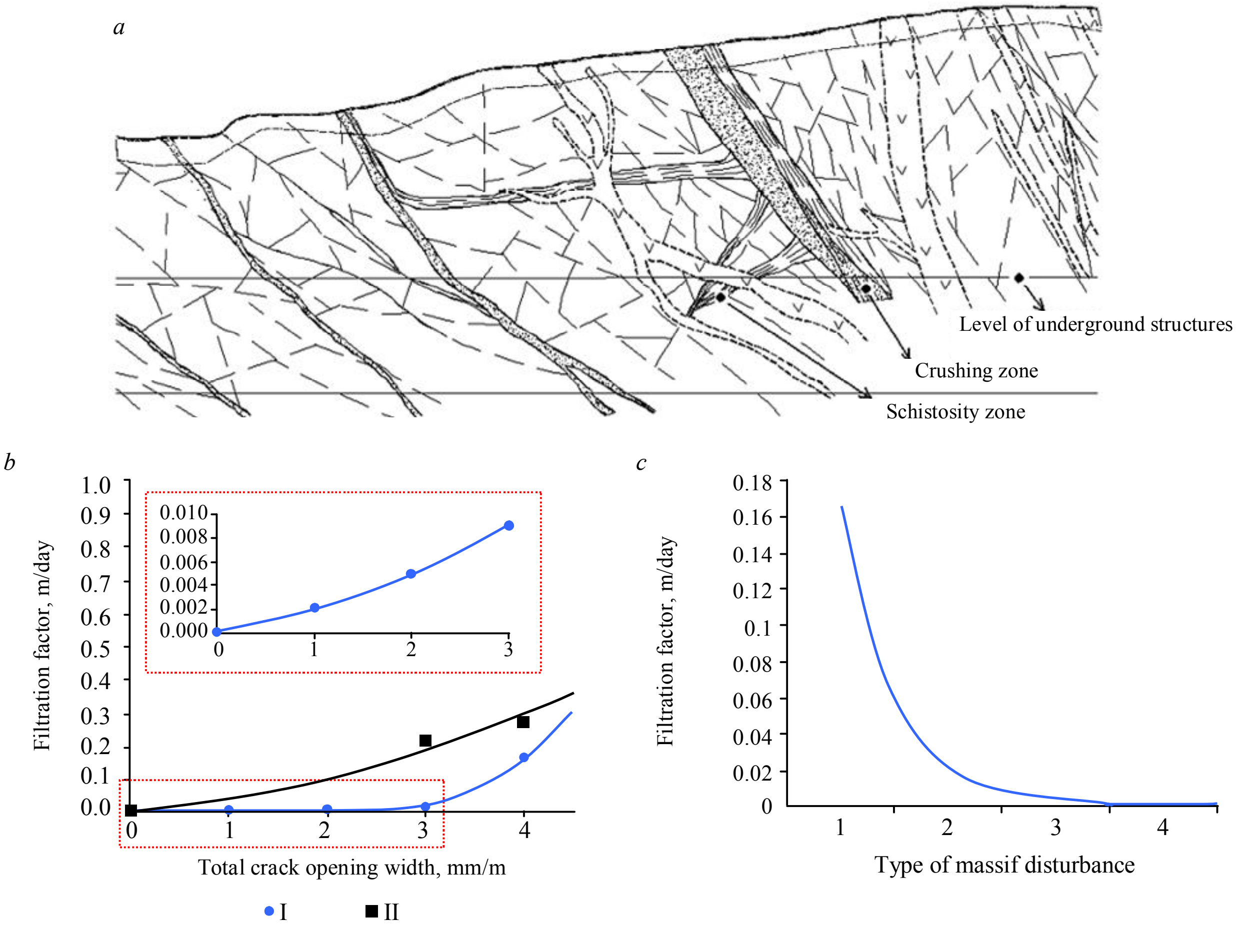

Fig.1. Structural and tectonic structure of a rock mass (*a*) and changing filtration characteristics of monolithic (*b*) and disturbed (*c*) sections of a massif depending on fracturing parameters

Filtration factor, experimentally obtained: at the Mining and Chemical Plant – I, at other rock objects – II
Massif disturbance: 1 – marginal zone of technogenic fracture; 2 – tectonic disturbance zones;
3 – contact of dikes with host rocks; 4 – slightly cracked gneisses

In relation to structural and tectonic elements of the rock mass model, the key parameters for formalizing mathematical models for calculating radionuclide output from the depth of an underground object were determined:

- the length of a migration path along the zones of tectonic disturbances of various orders to the border of an active water exchange area L (m);
- the velocity of groundwater movement in zones of tectonic and other disturbances V (m/year);
- annual water flow through 1 m^2 of a cross-section through violations at the depth of an object intended for waste disposal Q ($m^3/(m^2 \cdot year)$).

During the study, radionuclides were divided into several groups: short-lived radionuclide pollutants, long-lived, and natural ones. The simulation results confirmed the assumption that delay factors play a different role in various radionuclide groups. The results demonstrating the role of various factors in delaying the spread of radionuclide contamination are shown in the graphs (Fig.2, 3).

The graph (Fig.2) represents the dependencies of the maximum length of the migration path of various nuclides on the filtration and migration parameters obtained as a result of calculations.

Analysis of Fig.2 shows that the change in the filtration factor K_f has the most significant effect on the migration range of poorly sorbed short-lived (^{90}Sr) nuclides. For long-lived (^{99}Tc) radionuclides, including those with a high K_d distribution factor in the rock (^{239}Pu), a change in the filtration factor leads to an acceleration or deceleration of the migration process, while the maximum distribution halo does not change practically due to long periods of potential hazard

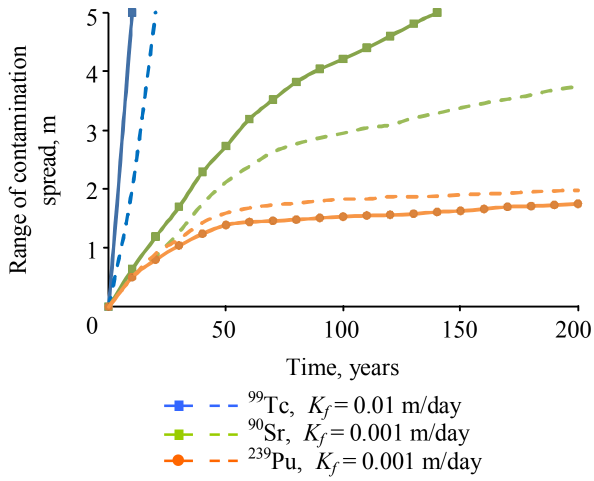

Fig.2. Dynamics of the spread of radionuclide contamination from the filtration parameters of the array

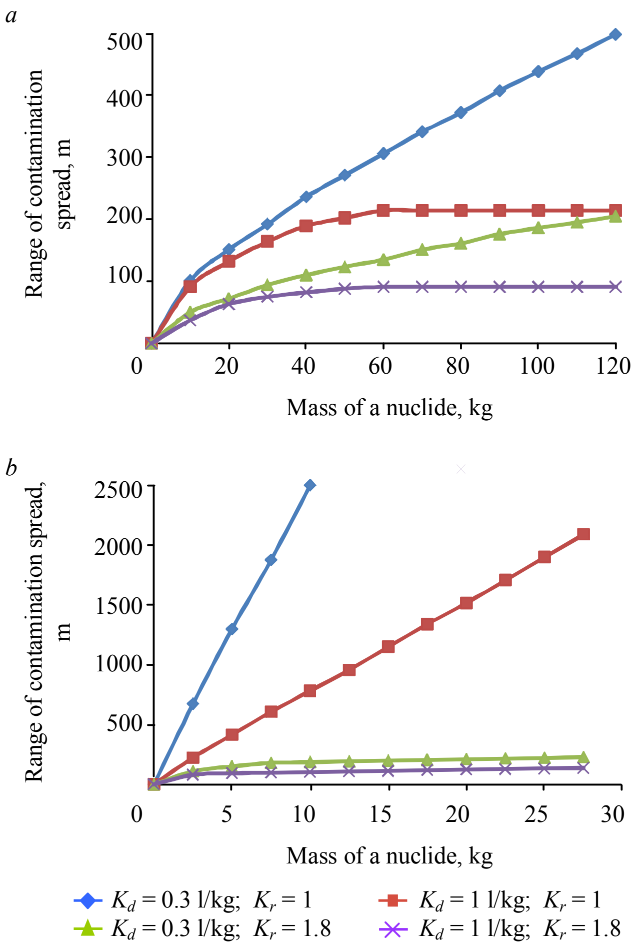

Fig.3. Dependence of the maximum length of a migration path ^{137}Cs (*a*) and ^{238}U (*b*) on the number of localized isotope and migration parameters

preservation. Thus, for long-lived nuclides, the parameters that determine the safety of disposal are the length of the contamination migration paths L_m and the parameters of the physical and chemical interaction K_d.

In order to establish the defining parameters for short-lived radionuclide contamination, an additional analysis of propagation was performed using the example of ^{137}Cs (Fig.3, *a*). The obtained dependencies for different values of migration parameters showed that for nuclides of this type, the “physical localization” factor (K_f) is even more prevalent than the “geochemical localization” factor (K_d). For any values of migration indicators of the environment (within the considered uncertainty intervals) and any initial quantities of isotopes of this type, they, as shown by the conducted safety analysis, cannot be a source of environmental danger for the considered burial conditions, since they will not leave the limits of the sanitary zone of deep disposal sites for radioactive waste in environmentally significant concentrations. The most important parameters, therefore, are the filtration factors and the parameters of physical and chemical interaction (K_f, K_d).

Figure 3, *b* shows the dependence of the maximum length of a migration path of natural isotopes on the number of localized isotopes and migration parameters on the example of ^{238}U. The physical meaning of the reduced value of the longitudinal dispersion factor (K_r = 1) lies in the possible presence of permeable zones of increased conductivity on the filtration path in the direction of surface watercourses that do not receive additional crack water. The results show that the maximum length of a migration path for natural isotopes does not depend much on the velocity of water filtration in the direction of the main distribution routes, which is explained by a long time of preservation of the potential danger of this radionuclide and is more determined by the ratio of their solubility and interference levels. The water balance indicators Q, the geometry of a filtration area n_0, the values of the hydrodispersion factors K_r determine the safety of isolation parameters of the geological environment for nuclides of this type.

The joint analysis of the obtained dependences showed that:

- the interfacial distribution factor K_d is one of the most important in ensuring the safety of long-term isolation of all types of radioactive waste. This determines the need for a detailed study of this indicator when isolating nuclides of all types;
- the volume of isolated waste is also a tool for managing the safety of the final isolation facility for all types of waste, with the exception of waste represented by short-lived nuclides.

Conclusions. One of the aspects of research planning in an URL is to establish a list of measured parameters and the necessary accuracy of measurement procedures. Increasing accuracy of measurement of all the parameters used in calculation procedures will only lead to an unreasonable increase in labor costs.

The approach proposed in this paper is to define the priority characteristics of a rock mass, which consists of using the method of sensitivity analysis, i.e. system change beyond the characteristics of the physical processes during the simulation of the safety of deep disposal sites for radioactive waste, to determine their impact on output indicators.

The results of the study made it possible to identify priority isolation mechanisms for different groups of nuclides and corresponding parameters of the geological environment that have the greatest impact on the safety of an RW disposal site and require high-precision measurements:

- for short-lived radionuclide contamination it is the “delay” (K_f, V_f);
- for radioactive waste containing long-lived radionuclides it is the “physical localization” (values of water flows to the burial chambers Q, thickness of filter zones h, hydrodispersion factor K_r) and the “geochemical localization” (K_d, sorption capacity, chemical composition of underground water, length of migration paths L for zones of permeability and open porosity n_o with convective migration mechanism);
- for natural radionuclides or waste with a low level of activity, it is the “deconcentration” (hydrogeological balance Q, the geometry of filtration paths).

The volume of waste to be isolated is also a tool for managing the safety of a final isolation facility.

REFERENCES

1. Abramov A.A., Beigul V.P. Creation of an underground research laboratory at the Yeniseisky site of the Nizhnekansky massif. URL: www.atomic-energy.ru/articles/2017/08/22/78690 (date of access 19.11.2018) (in Russian).
2. Gupalo V.S. Evaluation of long-term changes in the filtration characteristics of the zone of technogenic and natural fracturing of underground facilities for high-level waste. *Gornyi informatsionno-analiticheskii byulleten*. 2017. N 12, p. 115-121. DOI: 10.25018/0236-1493-2017-12-0-115-121 (in Russian).
3. The disposal of radioactive waste. Specific Safety Requirements No. SSR-5. IAEA Safety Standards. Vienna. IAEA, 2011, p. 104 (in Russian).
4. Malkovskii V.I., Yudintsev S.V., Gupalo V.S. Isolation of solid radioactive waste in near-surface storage facilities. Materialy XIX mezhdunar. konf. «Fiziko-khimicheskie i petrofizicheskie issledovaniya v naukakh o Zemle». Moscow: IGEM RAN. 2018, p. 226-229 (in Russian).
5. Linge I.I., Utkin S.S., Khamaza A.A., Sharafutdinov R.B. Experience in applying international requirements to justify the long-term safety of radioactive waste disposal facilities: problems and lessons. *Atomnaya energiya*. 2016. Vol. 120. N 4, p. 201-208 (in Russian).
6. Alexander W., Reijonen H., McKinley I. Natural analogues: studies of geological processes relevant to radioactive waste disposal in deep geological repositories. *Swiss Journal of Geosciences*. Vol. 108. 2015, p. 75-100. DOI: 10.1007/s00015-015-0187-y
7. Baghbanan A., Jing L. Hydraulic properties of fractured rock masses with correlated fracture length and aperture. *International Journal of Rock Mechanics and Mining Science*. 2007. Vol. 44(5), p. 704-719.
8. Blechschmidt I., Vomvoris S. Underground research facilities and rock laboratories for the development of geological disposal concepts and repository systems. Geological Repository Systems for Safe Disposal of Spent Nuclear Fuels and Radioactive Waste. Woodhead Pudlishing. Camdrige. 2010, p. 82-118.
9. Birkholzer J., Houseworth J., Tsang C. Geologic disposal of high-level radioactive waste: Status, key issues, and trends. *Annual Review of Environment and Resources*. 2012. Vol. 37, p. 79-106, DOI: 10.1146/annurev-environ-090611-143314
10. ISTC PROJECT #307B-97 Development of quantitative criteria for suitability of rock mass for safe long-term storage of waste from weapons-grade plutonium production, illustrated by Krasnoyarsk mining chemical combine, 2001.
11. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project, Vol. I, II. SKB Technical Report. 2011, TR-11-01. URL: skb.se/upload/publications/pdf/TR-11-01_vol1.pdf
12. Ohberg A., Rouhiainen P. Posiva groundwater flow measuring techniques. 2000. Posiva Reports. 2000-12, p. 87.

13. Raven K., Sterling S., Avis J. Geoscientific site characterization plan for the deep geologic repository at the Bruce site, Kincardine, Ontario. Avis Intera Engineering Ltd. URL: www.opg.com/generating-power/nuclear/nuclear-waste-management/Deep-Geologic-Repository/Documents/HPD/4.3.55_geoscientificsitecharacter.pdf]

14. Stober I., Bucher K. Hydraulic properties of the crystalline basement. *Hydrogeology Journal*. 2007. Vol. 15, p. 213-224.

15. Min K., Rutqvist J., Tsang C., Jing L. Stress dependent permeability of fractured rock masses a numerical study. *International Journal of Rock Mechanics and Mining Science*. 2004. Vol. 41(7), p. 1191-1210.

16. Tsang C., Neretnieks I., Tsang Y. Hydrologic issues associated with nuclear waste repositories. *Water Resources Research*. 2015. Vol. 51. Iss. 9, p. 6923-6972. DOI: org/10.1002/2015WR017641

17. Underground Research Laboratories OECD/NEA 2013. N 78122.

Author **Vladimir S. Gupalo,** *Doctor of Engineering Sciences*, *Professor*, *vs.gupalo@misis.ru* (*National University of Science and Technology* “*MISiS*”, *Moscow*, *Russia*).

The paper was received on 1 February, *2019.*

The paper was accepted for publication on 15 July, *2019.*