ASSESSMENT OF REQUIREMENTS TO THE GEOLOGICAL ENVIRONMENT FOR THE SUBSOIL SITING OF A RADIOACTIVE WASTE DISPOSAL FACILITY IN DEEP GEOLOGICAL FORMATIONS

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The paper analyzes the structure and the contents of main regulations on the subsoil siting of a deep geological radioactive waste disposal facility which was done based on the geological research performed to assess the Yeniseiskiy site in the Krasnoyarsk Territory. It also discusses some specific inconsistencies found in different documents, as well as ambiguities and inaccuracies in their content. The paper provides some recommendations on their upgrading.

Keywords: *radioactive waste, subsoil area, norms, recommendations.*

Introduction

To date, three decades of international research and the resulting knowledge accumulated have contributed to the opinion shared by the global scientific community and state authorities suggesting that deep (geological) disposal of radioactive waste (RW) can be considered safe [23]. This judgment found support in our country as well, which has accumulated a huge RW inventory over the years of nuclear confrontation. In 2011, enacted was the Federal Law No. 190-FZ of the Russian Federation On RW Management of July 11, 2011. Its provisions stipulate that "radioactive waste … shall be disposed of in RW disposal facilities" [19, Art. 12, p. 1]. At the same time, there is a specific note regarding the disposal of high-level and intermediate-level waste: "Solid high-level long-lived and solid intermediate-level long-lived radioactive waste shall be disposed of in deep disposal facilities for radioactive waste …" [19, Art. 12, p. 2]. Provisions of the law also state the depth criterion for the construction of deep RW disposal facilities (hereinafter referred to as DDFRW), which are viewed as "structures located at a depth of more than one hundred meters from the ground surface."

At present time, there are two key regulations containing the siting requirements that should be complied with during DDFRW establishment.

The first regulation, Radioactive Waste Disposal. Principles, Criteria and Basic Safety Requirements (NP-055-14) (hereinafter referred to as NP-055-14) was developed and approved by Rostechnadzor of Russia on August 22, 2014 according to order No. 379 [17]. It was registered with the Russian Ministry of Justice on February 2, 2015 (Order No. 35819). Therefore, norms and rules specified in NP-055-14 have a higher status and a binding effect.

The second regulation Methodological Recommendations on the Decision-Making Supporting

Subsoil Site Selection for Non-Mining Purposes [10] was developed by the Federal Budgetary Institution State Commission on Mineral Reserves (FBU GKZ) run by the Federal Agency for Subsoil Use (Rosnedra) of the Ministry of Natural Resources and Ecology of the Russian Federation (MPR). The above Methodological Recommendations … (hereinafter referred to as MR-2007) were proposed for application under the Protocol of the Ministry of Natural Resources of April 03, 2007 No. 11-17/0044-pr. Basically the MR-2007 provisions are of a recommendatory nature, however, this document serves a basis for the Rosnedra in making its decisions on the suitability of a selected subsoil site for the underground RW disposal in deep geological formations.

It should be emphasized that both of these documents are not based on proven theoretical concepts or reliable empirical solutions, as those applied to estimate the mineral reserve inventories. These are mainly based on common sense and the most general ideas regarding the influence produced by various elements of the geological environment on deep RW disposal conditions. This is explained by the fact that Russia has no hands-on experience in deep RW disposal, whereas rather limited experience associated with such activities is available abroad [23].

The paper considers and analyzes the requirements that were stipulated for the geological environment of deep formations in both of the above documents [10, 17]. The experience obtained from the geological study of the Yeniseiskiy site (Nizhnekanskiy massif, the Krasnoyarsk Territory) [1, 9, 12] was used in this case. In this analysis, of main focus was the validity of the requirements, their interrelation, the clarity and unambiguity of concepts and criteria suggested.

Seismicity and volcanism, which are very specific areas of knowledge, were not considered in this article.

Analysis of the regulations

Global geostructural siting of deep disposal sites. The aforementioned regulations [10, 17] do not impose any restrictions on the DDF RW location within the geological structures of various ages and genesis. Ancient platforms (cratons), young platforms (plates), mobile belts (orogens), their separate fragments (terrains), all of them are considered suitable for DDFRW siting. Indeed, DDFRW and underground laboratories established to study the deep RW disposal concept have been sited in various structures [20]. We believe that the regulations should discuss large geological structures that are to be considered unfavorable for DDF RW siting purposes, including: boundaries of lithospheric plates and large geological regions – zones of spreading, subduction and collisions, in particular, rifts, sutures, deep faults regardless of their activity. At the same time, apparently, it can be considered advisable to provide certain recommendations regarding the minimum permissible distance between the disposal facilities and the specified geostructural zones.

Local structural and geological siting of DDFRW. In general, both of the above regulations [10, 17] contain rather specific, but not always unambiguously understandable restrictions on DDFRW siting within some local geological structures. Basically, the restrictions relate to the areas of disjunctive disturbances, mainly to *active faults,* as well as to "*active geodynamic zones.*"

Thus, NP-055-14 [17, p. 48] prohibits DDFRW siting "*on sites located directly on active faults or in active geodynamic zones.*" Methodological recommendations of FBU GKZ [10, p. 3.3 .15] also suggest that "*active discontinuous faults*" are seen as unfavorable conditions for underground construction.

The term *active fault* was introduced into modern science in 1949 by American seismologist Robert E. Wallace, who provided it with the following definition: "*active fault* is a fault in the earth's crust or the entire lithosphere, along which displacements occurred or earthquake foci were localized in the historical time or in the Holocene (last 10 thousand years)" [3].

However, quite different definition of this term can be found in the regulations. At the same time, different operating documents of Rostekhnadzor and the Ministry of Construction indicate different time periods for the fault activation (from 100 thousand to 2 million years ago), as well as various rates of rock block displacements (from 0.5 m to an uncertain level that can "*undermine the safety of structures*") [15, 16, 18].

Such terminological arbitrariness in the definitions of active fault is believed to be associated with the overreach of state ministries and services. Relevant regulations of Rostekhnadzor and the Ministry of Construction do not provide them with a right of giving definitions to terms associated with geological structures and the quantitative indicators characterizing them. In terms of functional responsibilities, the subsoil and the geological structures located in them appear to be under the jurisdiction of the Ministry of Natural Resources (Federal Agency for Subsoil Use). However, their powers do not provide for the development and approval of normative definitions relating to the content of geological structures. Of course, it is necessary to overcome the arbitrary interpretation of the terms being considered essential for the safety of industrial facilities and the population of the country. Therefore, the term active fault should be provided with a scientifically grounded unambiguous interpretation recognized by all interested departments.

In addition to the term *active fault*, the regulations also consider *active geodynamic zones*, within which DDFRW construction shall be prohibited [17, p. 48]. This concept also requires a clear and unambiguous formulation.

Lithological (petrographic) composition of rocks. The considered regulations (NP-055-14 and MR-2007) discuss approximately the same rocks seen as suitable for RW disposal purposes (Table 1). At the same time, MR-2007 requirements apply to all types of solid waste, including the radioactive waste.

Table 1. Rocks considered suitable for RW disposal

NP-055-14 [17]	MR-22007 [10]
"53...host rocks should fall into one of the potentially suitable types (crystalline igneous or metamorphic rocks, including granites, gneisses, tuffs, preferably of basic or ultrabasic composition; rock salt or anhydrite; clays)"	*"3.1.2.4. Suitable for solid waste disposal at purposely constructed underground facilities are considered... subsoil areas constituting of practically impermeable rocks (clays, rock salt, non-fractured igneous rocks), excluding the contact of waste with groundwater*

NP-055-14 presents a wider range of potentially suitable bedrocks as compared with MR-2007. In particular, the FBU GKZ document does not mention metamorphic, tuffaceous rocks and anhydrites at all, which gives formal grounds not to consider subsoil areas in these rocks during the state geological examination.

It should be emphasized that the Yeniseiskiy site was exactly identified and evaluated as part of a metamorphic rock mass (Archean gneisses). The state examination performed under the appraisal geological explorations in this area was implemented by FBU GKZ with its results approved by Rosnedra [9]. In this case, the experts, apparently, were guided by some common sense and by relevant considerations regarding the potential feasibility. Thus, the Methodological Recommendations of FBU GKZ [10] need some clarification to expand the list of rocks to be considered potentially suitable for RW disposal.

RW disposal depth. As mentioned above, according to the Federal Law No. 190-FZ On Radioactive Waste Management ..., a deep disposal facility for radioactive waste includes *"a structure located at a depth of more than one hundred meters from the earth's surface"* [19]. In NP-055-14, the disposal depths are neither regulated nor classified. At the same time, MR-2007 proposes a depth-wise siting classification: *"Facilities designed for the underground disposal of solid and solidified waste (UDF SRW) can be categorized by depth either as deep UDF SRW (300—1,500 m) or near-surface shallow UDF SRW (up to 300 m)"* [10]. This regulatory provision contradicts the Federal Law, according to which all structures located deeper than 100 m should be considered deep, therefore the provisions of this regulatory document of the Ministry of Natural Resources [10] require some harmonization with the Federal Law.

Hydrogeological conditions. According to MR-2007, *"physical, mechanical, thermophysical and filtration properties of the rocks should be considered as the main characteristics supporting the siting decisions and the selected design features of purposely-designed underground disposal facilities for solid waste."* At the same time, *"hydrogeological conditions (the presence of ground water, its chemical composition, aggressiveness towards metal structures, cable sheaths and concrete, water availability and rock permeability, distribution of groundwater heads) are considered among the main factors governing the conditions for the construction of underground structures".* According to MR-2007 provisions, from the hydrogeological point of view, areas prone to *"catastrophic breakthroughs of groundwater with large inflows of water into the excavations"* should be considered unsuitable [10].

Basically, quite similar requirements were set forth in p. 53 of NP-055-14: *"aquifers, groundwater lenses or fractured zones, through which water inflow into the underground excavations and their flooding can occur, should not be present within the rock mass."*

However, unfortunately, these regulations provide no specific requirements regarding the rock permeability. According to p. 53 NP-055-14, *"neither lenses of brines nor layers of permeable rocks should be present within the mining allotment"*, while preference should be given to those subsoil areas where *"the aquifers considered impermeable and unsuitable for water supply are located above the estimated depth of the RWDF structures"* [17, p. 54].

We believe that the regulations should provide relevant requirements regarding the permeability not only of the target interval intended for RW disposal, but also the one of the supra-target and subtarget horizons. The complexity of the conditions and underground saturation of the excavations is highly dependent on the saturation of the overlying sediments. In addition, given the great disposal depths, in the underlying strata, large pressure heads are inevitably formed on the bottom of the excavations. Therefore, it seems reasonable to include the recommendations regarding the preferred subsoil areas in which the overlying and underlying strata are represented by watertight or weakly permeable rocks to the above regulations.

Moreover, the definitions of these rocks should be given in the regulations. According to GOST 25100-2011 with its provisions applied under the engineering surveys performed at the construction stage, soils with a water permeability coefficient of less than 0.005 $m \cdot day^{-1}$ should be considered as water-impermeable. The permeability coefficient of low-permeability soils should fall in the range from 0.005 to 0.03 $m \cdot day^{-1}$ [6]. Human engineering and economic activities are mainly implemented in near-surface conditions, for which the above regulatory permeability coefficient thresholds can be apparently considered valid.

Construction-based permeability classification system from GOST 25100-2011 was applied in the hydrogeological study of the Yeniseiskiy subsoil area, which resulted in a positive expert statement from Rosnedra [9, 12]. However, when it comes to the formal application of the threshold permeability coefficients, some contradiction with the actually observed hydrogeological conditions can be noticed. Although the permeability of the Archean rock massif of the Yeniseiskiy area appears to be very low (the median value of the filtration coefficient accounts for 0.0004 $m \cdot day^{-1}$), the massif cannot be considered as being absolutely waterproof. Extremely slow water flows are observed in it (at great depths also), which is confirmed by hydroisohypsum maps, the regime observations, and the chemical and isotopic composition of groundwater. At the same time, due to the very small size and cracks, the groundwater flow mechanism involves some capillary and viscous forces, which can quite badly distort the classical filtration mode described by the Darcy law [12].

At other subsoil facilities, some other permeability criteria are recognized for the deep sections. Thus, for oil and gas fields usually located at great depths reaching the first kilometers, a threshold of 1 mD (about 0.00086 $m \cdot day^{-1}$ at 20 °C) is considered. If the permeability exceeds 1 mD, the rock is considered as a reservoir; otherwise, it is considered as a confining layer [22]. Thus, according to the criteria provided in GOST 25100-2011 considering near-surface conditions, the deep horizons of many hydrocarbon fields are considered as poorly permeable or impermeable.

The research performed at the Yeniseiskiy site has shown that considering the deep disposal conditions to be established at the DDFRW site, a special system of rock classification by the permeability level depending on the DDFRW depth and on the petrographic (lithological) type should be developed. Most researchers consider evaporites (rock salt, anhydrite, gypsum) as impermeable rocks. The water permeability of pelites (clays and mudstones) varies within a range of $1 \cdot 10^{-7}$—$1 \cdot 10^{-6}$ D. However, at a depth of 1,500 m, where the temperature is 50—60 °C, the permeability of clayey rocks increases significantly [4]. Even at great depths, crystalline rocks have higher and more varied permeability than the clay rocks [12, 21, 24].

In terms of their spatial position in the subsoil, mining and geological conditions of construction, the hydrogeological and engineering-geological conditions, deep RW disposal facilities appear to be most similar to sedimentary or stratiform deposits of solid minerals. At the same time, the target RW disposal interval can be viewed as an analogue of a stratal mineral deposit.

Considering the alikeness of the sites proposed for DDFRW construction and these deposits, the application of an analogy method is seen as perfectly legitimate to evaluate the geological and hydrogeological suitability of the studied subsoil areas. Thus, when the hydrogeological conditions at solid mineral deposits are investigated, *"relevant research is performed within the prospecting deposit… and the adjacent territory." "Hydrogeological study is performed in the area associated with potential drainage effect produced by drainage and drainage systems considering the boundaries of the main aquifers"* [8].

This statement is supported by the fact that the main water inflow enters the underground excavations from the drainage zone, the size of which depends on the radius of the depression funnel, which significantly exceeds the size of the excavations.

Another important aspect is that radionuclide migration from the DDFRW, in case of radionuclide release with groundwater flow, will occur outside the repository site. Flow-driven migration of radionuclides and its forecasts are important and necessary to consider for the outer zone of the repository and not its underground section. For this reason, filtration and migration parameters of the geological environment outside the DDFRW site, in the zone of water inflow formation and along the paths of possible flow-driven radionuclide migration should be studied.

MR-2007 provisions require to explore a subsoil plot considering a much larger area than the area occupied by DDFRW structures: *"the area of a subsoil plot proposed for the construction of an underground structure should be 2.5—3 times larger than the estimated useful (excavation) area of the facility."* NP-055-14 (paragraphs 34—36) provides a very vague statement regarding this condition: it refers to the concepts of "a site" and "an area", however the size ratios of these spatial objects were not indicated. Therefore, the initiators of the siting activity are free to apply arbitrary dimensions, which makes the study of the site and the assessment of its suitability for RW disposal purposes incomplete and insufficiently objective.

We believe that the regulations should include a requirement on a hydrogeological study of RW disposal sites covering a zone within the potential radius of the drainage effect that can be produced by drainage and drainage systems of the underground structure, as well as within the radius of potential radionuclide migration.

Relationship with surface water bodies. Unfortunately, none of the above regulations provide any regulatory requirements regarding relative position of the underground structure and surface water bodies (rivers and lakes). Considering the great depths assumed under DDFRW designs, shallow water bodies can be disregarded. However, large rivers are quite rightly considered dangerous for underground excavations, affecting the flooding conditions or catastrophic breakthroughs [2, 11]. Therefore, it seems advisable to introduce the maximum permissible distances between DDFRW and large or medium-sized rivers with an average flow rate of more than 100 $m^3 \cdot s^{-1}$.

Thermophysical properties of rocks. As already mentioned above, according to MR-2007 provisions, thermophysical rock properties are considered as the main characteristics supporting the choice of subsoil sites proposed for underground RW disposal facility construction. Nevertheless, NP-055-14 (p. 31) provides only the most general requirements in this regard: *"the rocks enclosing DDFRW shall be resistant to the thermal effect of heat-generating RW, retain their insulating properties and provide a thermal mode that would not cause the failure of the engineered safety barriers."*

Under the geological studies, thermophysical properties and their assessment appears to be essential for the disposal of high-level waste (HLW) characterized by high heat release. It is a common fact that rocks tend to be poor heat conductors. Therefore, it is expected that the rocks with relatively increased thermal conductivity (l) will remove the heat from HLW into the surrounding subsoil, while in case of rocks with low thermal conductivity the waste may be overheated, as well as the barrier materials, surrounding rocks and groundwater. The rocks recommended for RW disposal are characterized by a wide range of thermal conductivity levels (Table 2). In contrast to monolithic rocks, fractured and porous types of rocks with their cavities filled with water ($\lambda = 0.6$ $W \cdot m^{-1} \cdot K^{-1}$) and (or) air ($\lambda = 0.022$ $W \cdot m^{-1} \cdot K^{-1}$) are characterized by significantly lower thermal conductivity and, apparently, are considered unfavorable for HLW disposal purposes [13].

Table 2. Thermal conductivity of rocks recommended for RW disposal purposes [7]

Rocks	Thermal conductivity factor (λ), $W \cdot m^{-1} \cdot K^{-1}$
Anhydrite	2.5...5.8
Clay	0.1...3
Gneisses	0.9...4.9
Granite	1.1...3.9
Rock salt	1.7...5.5
Tuffs	1.3...4.0

As regards the deep HLW disposal option, in addition to the study of the lithological (petrographic) rock composition, NP-055-14 is recommended to include some provisions stating that the study of thermophysical rock properties should be considered as a must and to establish the lower permissible thermal conductivity limit.

We believe that the NP-055-14 requirement stating that the host rocks should be resistant to thermal effects and preserve their insulating properties has to be supplemented with the conditions to be considered under the study of the thermal effects produced on the rock properties. Experiments during which the gneisses rocks of the Yeniseiskiy site were heated to 120 °C have shown that a change in the rock strength occurs more often: in 42 % of cases the strength increases, in 25 % it decreases and only in 33 % it remains the same. The above changes in the rock strength are probably associated with the changes in the thermally stressed state of the rocks [5].

Conclusion

Provisions of NP-055-14 and MP-2007 setting up the requirements for the geological environment of subsoil areas proposed for RW disposal purposes were analyzed revealing some flaws in their content emphasized in this article.

The imperfection of regulatory documents imposes a great burden of moral responsibility on the researchers being responsible for the decisions based on which the RW disposal project is going to be actually implemented. Is it possible to argue that a decision made based on imperfect regulations can provide the DDFRW safety in the future? Apparently, the answer is no. At the current stage, we can only talk about the *formal compliance* of the studied subsoil area with the requirements of state authorities, but even while making a difficult decision about some formal compliance *"we should be always conscious of our fallibility"* [14].

It worth noting here that the subsoil areas, the barrier properties of which would fully provide the long-term safety of the disposal facility, apparently do not exist at all. Therefore, the natural capabilities of the geological environment should be supplemented and brought to acceptable conditions by appropriate design solutions reflected in the structure of the engineered safety barriers.

Despite their flaws, the existing regulations provide a practical basis for the decision-making, relevant discussions of the results obtained and further improvement of the requirements. Based on this starting point, specialists and scientists can move forward in their study of the geological environment at DDFRW sites along with the development of theoretical approaches that *"tend to increasingly approach the truth"* [14]. We hope that the regulations evolve with time along with the plans drawn regarding the RW disposal activities and their implementation.

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