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# Formation selection methodology for deep geological repository in Lithuania

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**Abstract**. A special program and action plan have been developed in Lithuania for the purpose of implementing the European Council Directive 2011/70/Euratom of 19 July 2011, establishing the Community framework for the responsible and safe management of spent fuel and radioactive waste. An important part of this plan is related to geological investigations for the site selection, design and construction of deep geological repository (DGR) for spent nuclear fuel and high-level long-lived radioactive wastes. The main task of geological investigations is to select a suitable geological environment for DGR, which is closely related to that of the DGR site. There are several alternative geological formations potentially suitable for DGR in Lithuania. Selection of the most suitable DGR site should be made and the DGR concept should be developed applying clear methodology. The proposed methodology is based on the safety requirements established by International Atomic Energy Agency (IAEA), systematic approach and criteria that are widely used worldwide. The suitability evaluation criteria are divided into 4 groups according to the factors responsible for the stability and safety of the DGR system. The highest rank of significance is assigned to the group of criteria that are associated with the factors responsible for the loss of the long-term stability of the system. The criteria associated with the DGR system confinement are assigned to the second group and are ranked second in significance. The third group of evaluation criteria could be characterized as a data availability group. It consists of the evaluation criteria associated with the emergence of uncertainties. Features or processes responsible for the improvement of formation properties over time are assigned to the fourth group and have the lowest rank of significance. The application of this methodology allows calculating the suitability score of each potentially suitable geological formation depending on the level of data detail at any stage of the investigation.

***Key words***: *radioactive waste, criteria, formation suitability, significance rank, suitability score*

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## INTRODUCTION

Since the beginning of the Ignalina Nuclear Power Plant (INPP) operation in 1983, all spent nuclear fuel and radioactive waste has been stored at the INPP site. INPP is located at the North-eastern edge of the territory of Lithuania. Removal of spent nuclear fuel from special water ponds where it had been stored, its loading into CASTOR RBMK-1500 or CONSTOR RBMK-1500 casks and transportation to an interim storage facility on the industrial territory of the INPP have been carried out since May 1999. Spent nuclear fuel (SNF) can be stored in these casks for 50 years. Almost half of this period has already passed. This makes the elaboration of the SNF final disposal option very important. Direct disposal of SNF, which is assigned to radioactive waste, is provided for in Lithuanian legislation. The European Council Directive 2011/70/Euratom of 19 July 2011 establishing the Community framework for the responsible and safe management of spent fuel and radioactive waste (Directive) is in force in all member states of the European Union. According to this Directive, all radioactive waste has to be managed and finally disposed of on the territory of the country where it was generated. For the implementation of this Directive, a special program and action plan of radioactive waste management have been developed in Lithuania. In Lithuania, the design and construction of a deep geological repository (DGR) for spent nuclear fuel and high-level long-lived radioactive waste is scheduled for 2067. In accordance with Safety Standards of the International Atomic Energy Agency (IAEA), safety of the DGR should be ensured by a multi barrier system, which consists of man-made (engineered) and natural barriers operating together in a complementary way to provide isolation and containment of radioactive waste. The first barrier of the DGR system is represented by a matrix where radioactive waste is confined, the second one by a corrosion-resistant container, the third one by backfill with high sorption capacity, and the last one is represented by a suitable geological formation. A comprehensive DGR project has been carried out by INPP since 2019. A large part of this project is related to geological investigations and Lithuanian Geological Survey is responsible for the implementation of this part of the DGR project. The aim of the investigations to be pursued in the coming decade is to select the geological environment and several alternative sites suitable for the DGR installation.

Several geological desktop studies dealing with the conceptual planning stage of the DGR site selection were performed during the period 1998–2014. The main outcome of these studies is the location of several potentially suitable formations for the DGR installation in the geological setting of Lithuania. Lithuanian formations of Proterozoic crystalline basement rocks, lower Cambrian clays, Permian evaporites (rock salt and anhydrite) and lower Triassic clays were identified as potentially suitable for DGR. Potential suitability was determined according to the petrological structure and geometry of formations. Based on the large amount of borehole data stored in the Lithuanian State geological information system GEOLIS, the areas of the potentially suitable formations' occurrence were determined. Further analysis of all possible alternatives requires elaborating four different disposal concepts. For economic and time saving purposes, it is more reasonable to select one or two most suitable geological formations in the process of the DGR concept development and then to select several alternative sites for further investigations. The suitability of the geological formations should be evaluated according to the DGR safety and performance assessment criteria. A clear methodology or technique is needed to perform such evaluation. The DGR design and construction is a very long-lasting process. Therefore, methodology should be simple enough for the present-day and future political decision-makers to comprehend.

The proposed methodology relies on the safety requirements and recommendations established by the IAEA (IAEA 1994, 2011). The systematic approach, universally applicable criteria (Mallants *et al*. 2018) and multiple criteria analysis form the basis of the proposed methodology.

## GENERAL REQUIREMENTS FOR THE DGR INSTALLATION

DGR is a complex system of surface and underground structures consisting of the geological environment and technological installations. Selection of the geological formation and site for DGR should be based on principles of radiation protection and responsibility towards future generations. These principles were set by IAEA (IAEA 1981) in the eighth decade of the last century. According to these principles, people should be protected throughout the period of time during which waste remains potentially hazardous, and future generations should not have to bear the costs or suffer harmful consequences of the applied necessary measures to ensure protection of man and his environment.

The purpose of the DGR installation is to isolate radioactive waste from the human environment. The isolation of radioactive waste and human environment protection should be achieved by using a multi-barrier system, which consists of engineered and natural barriers, complementing each other in fulfilling safety functions.

The DGR should be installed deep enough and should not appear near the land surface because of geological processes during the period of time while the radioactivity of the waste exceeds the admissible level. In addition, the geological formation should be thick enough to provide a sufficient buffer zone between the DGR and the boundaries of overlying and underlying strata or tectonic zones. The geological structure where the DGR is planned to be installed and the structures surrounding it could be considered as the DGR system. The system should remain stable until waste becomes harmless to the human environment. The walls of underground openings should be isolated and investigation boreholes should be sealed to avoid the radionuclide release into the human environment. To avoid potential mechanical damage to the DGR system, it should be installed at a site where the exploration of mineral resources is not expedient.

**Table 1** Geological factors related to the main requirements

| Requirements for the geological formation | Geological factors |
|---|---|
| 1. Appropriate engineering geological conditions | 1) Sufficient depth;<br>2) physical and mechanical, thermal and other properties of rocks;<br>3) sufficient thickness of geological formation. |
| 2. Long-term stability of the DGR system | 1) Stable tectonic conditions;<br>2) formation resistance to climate impacts;<br>3) no recent and future mineral resources exploration;<br>4) low seismicity in the area;<br>5) no recent earth crust movements;<br>6) very low possibility of volcanic activity. |
| 3. Appropriate isolating properties of the DGR environment | 1) No hydraulic connection between land surface and DGR excavations;<br>2) very slow groundwater or moisture movement;<br>3) suitable and stable hydro-chemical conditions;<br>4) retardation of radionuclide migration within the geological formation. |
| 4. Radionuclide retardation possibility due to geological factors or DGR impact | 1) Processes causing lower permeability of rocks (self-sealing of fractures, rise of new minerals etc.);<br>2) processes causing higher sorption capacity;<br>3) processes maintaining reduction conditions. |

In order to avoid rapid radionuclide transport from waste packages to the environment, it is essential that there would be no groundwater flow in the geological formation, where the DGR is going to be installed. Unwanted chemical reactions between radioactive waste and groundwater as well as retardation of radionuclides should be anticipated. DGR engineering constructions should be resistant both to thermal and radioactive impacts. Geological factors related to the above-mentioned requirements are presented in Table 1.

## METHODOLOGY OF GEOLOGICAL FORMATION SELECTION

Selecting a geological formation for DGR is the task of finding some optimal conditions for the latter. To solve this task, it is necessary to make a decision at each stage of evaluation. In many cases, decisions could be subjective and could depend on different opinions of decision-makers. To prevent possible subjectivity in decision-making, methodology for suitability evaluation should be followed. The suggested methodology is based on principles of the analytic hierarchy process (AHP) (Saaty 1995; Mendoza 1997; He *et al*. 2020) and multicriteria evaluation (MCE) (Hoseini, Kamrani 2018). Each geological factor could be characterized by one or several criteria and one criterion could characterize several factors. For example, the factor “suitable properties of rocks” could be characterized by the bulk density, thermal conductivity, compressive strength and other parameters used as criteria. On the other hand, the criterion “permeability of rocks” is related to the factors of the system’s isolating properties and that of the radionuclide retardation possibility.

### Importance of the possible events and processes for the DGR system performance

When installing the DGR, situations of system instability, fast accidental release of radionuclides from the repository and unpredictable performance of the system should be avoided. When caused by geological factors, such situations could be referred to as scenarios of the DGR performance. For example, an intensive tectonic uplift could cause the emergence of a geological formation on the land surface. Active faulting could damage the engineered constructions or cause the appearance of fractured zones functioning as gas and fluid transport pathways within geological formations.

In terms of DGR constructability and long-term safety, DGR performance scenarios differ in significance. The most significant scenarios are those that cause mechanical damage to the DGR system or its collapse. Such scenarios could be evaluated as catastrophic. Another group of scenarios includes those that could cause accidental fast release of radionuclides from the DGR system and, therefore, they could be rated as accidental scenarios. A scenario of unpredictable consequences is the one that is caused by a geological factor that has not been sufficiently investigated yet or the changes it has induced in some features cannot be predicted for a long period of time. Such scenarios could be termed scenarios of uncertainties and could be assigned to the third group of significance. There are several geological factors that can improve mechanical or hydraulic properties of geological formations, e.g., self-sealing of fractures. Scenarios caused by such geological factors fall into the fourth group of scenarios (Table 2). The rank of significance assigned to the groups of geological factors and criteria corresponds to that of the DGR performance, and is used as a multiplier coefficient with values ranging from 4 to 1 in the final formula for suitability evaluation (1).

## Criteria for the geological formation selection

Each feature, event or process that is characteristic of a certain geological environment and is important to stability and safety of the DGR system could be used as a criterion for selecting a formation or site suitable for the DGR installation. According to IAEA, the criterion is the condition on which a decision or judgement can be based (IAEA 1994). It may be qualitative or quantitative and should result from established principles and standards.

Selection of the geological formation and site for the DGR installation should be performed according to the relevant criteria characteristic of a certain geological factor and satisfying the above-mentioned requirements for the DGR constructability and long-term safety. In accordance with global practice, each criterion should be obtained from the results of relevant investigations or should be qualitatively evaluated and accepted by several professional experts. It is possible to compare the suitability of different geological formations for the DGR installation if each formation has been evaluated applying the same set of criteria.

Geological criteria related to important geological factors and grouped by significance rank are presented in Table 2.

Significance rank is assigned to each criterion within a group, and when calculating the final suitability score (SS) of the geological formation, the suitability index (SUI) of each criterion will be multiplied by 4, 3, 2, or 1.

Another task of the geological formations' suitability evaluation is to determine the importance of each criterion in relation to other criteria of the same group, which could be called weighting of criteria (Ahlroth *et al*. 2011, Iwaro *et al*. 2014). There are several weighting methods described in literature (Odu 2019). The pair-wise comparison method seems to be applicable for the proposed methodology. It is the method where the decision-maker compares each criterion with the other ones and determines the level of preferences for each pair of such criteria. The total weight of all criteria in one group is equated to 1. The weight of each criterion could be understood as part or percentage of the total weight of the criterion group.

The suitability index should be provided for each value or interval of the parameter (criterion) that is obtained from the results of investigations or is determined qualitatively. Each value of the first group criteria is given an index ranging from 5 (very suitable) to 0 (unsuitable). Zero suitability, which means unsuitable and excludes the formation under analysis from further evaluation, could be assigned to the criteria of the first group. In the case of the DGR installation, zero suitability will denote the geological formation where the catastrophic scenario of performance is highly possible. Indexes ranging from 4 (suitable) to 1 (least suitable) should be given to criteria of the second group, from 3 (suitable) to 1 (least suitable) – to those of the third group and 2 (suitable) or 1 (least suitable) – to the fourth group of criteria. When quantitative values of parameters are available, suitability indexes should be given to certain inter-

**Table 2** Criteria grouped by DGR performance scenarios

| Value of the significance rank (SR) | Scenario of DGR performance | Criteria for evaluation |
|---|---|---|
| 4 | Mechanical damage of DGR system (catastrophic). | 1. Sufficient strength.<br>2. Formation dimensions.<br>3. Seismic activity.<br>4. Occurrence of active faults.<br>5. Temperature.<br>6. Tectonic regime.<br>7. Velocity of vertical movement.<br>8. Mineral resources. |
| 3 | Fast release of radionuclides from DGR system caused by migration of groundwater or gases (accidental). | 1. Occurrence of waterproof rocks.<br>2. Hydrodynamic regime of the saturated zone.<br>3. Distance from discharge areas.<br>4. Radionuclide solubility in groundwater.<br>5. Occurrence of rocks with high sorption capacity (above the DGR system). |
| 2 | Uncertainties in radionuclides' migration predictions (unpredictable). | 1. Structure of groundwater or gas flow.<br>2. Climate impact on DGR system.<br>3. Glaciation impact on DGR system. |
| 1 | Radionuclide retardation increase in the DGR system (improvement). | 1. Layering of sedimentary cover.<br>2. Occurrence of basal rocks.<br>3. Self-sealing of the fractures. |

vals of parameters. For example, quantitative values of the first group criterion “depth of the formation” could be easily obtained from the borehole data and, based on the evaluations performed in various countries, suitability of intervals could be determined. The optimum depth in the interval between 500 and 700 meters is evaluated as very suitable (suitability index 5). The depth interval from 200 to 500 m is rated as suitable (3), more than 700 m as less suitable (2), an uninvestigated depth interval as least suitable (1) and the depth interval less than 200 m is evaluated as unsuitable (0).

## POTENTIALLY SUITABLE FORMATIONS IN LITHUANIA

The geological structure of Lithuania could be suitable for the DGR installation. The territory of Lithuania is located in the North-eastern part of the East European platform. Crystalline basement occurs at a depth of 200–2300 meters below the land surface. The sedimentary cover consists of the deposits of all geological systems. Ediacaran and Cambrian deposits are siliciclastic (claystone, clay, gravelstone, sandstone, siltstone), Ordovician and Silurian deposits are carbonate and clayey (limestone, marl, dolomitic marl, dolomite, claystone, clay), Devonian deposits are carbonate, sandy and clayey (sandstone, sand, clay, dolomitic marl, dolomite, etc.), Carboniferous deposits are sandy and clayey, Permian deposits are represented, in general, by limestone, anhydrite and rock-salt, Triassic deposits are clayey, Jurassic deposits are represented by clay, siltstone, sandstone, those of Palaeogene and Neogene by sand, silt, clay and Quaternary deposits are represented by till, sand and gravel.

From the hydrogeological point of view, the territory of Lithuania belongs to the Baltic artesian basin (BAB), which is located in the East European platform. In the North and West, the basin borders on the Baltic shield. Its eastern boundary runs alongside lakes Chudo and Pskov towards the centre of Belarusian–Masurian Highlands. The southern boundary of the basin coincides with the platform edge faults. Several structural elements, i.e., the Baltic depression, the slope of the Baltic shield, and the Belarusian–Masurian Anteclise are distinguishable in BAB. Groundwater of BAB occurs in the sedimentary cover and in fractured rocks of the crystalline basement. Groundwater forming processes are predetermined by the above-mentioned structural geological features as well as by climate conditions, relief and river drainage of the region (Kanopienė *et al*. 2005).

Based on the results of the classical geological investigations stored in the Lithuanian state geological information system, recommendations provided in IAEA publications and best international practices, several geological formations were evaluated as potentially suitable for the DGR installation. They are as follows: 1) rocks of Crystalline basement, 2) Lower Cambrian clay; 3) Permian evaporites; 4) Lower Triassic clay.

**Rocks of Crystalline basement.** In Lithuania, the Crystalline basement occurs at a depth of 200–2300 meters below the land surface and is represented by Proterozoic rocks: metamorphosed granulite facies in Western Lithuania (gneisses, schists, enderbites, charnokites) and amphibolite facies in the Eastern part of Lithuanian territory (amphibolites, gneisses, granites). There are intrusions of basic rocks (gabbro, diabases) in the Crystalline basement rocks. Only rocks of the Eastern and South-Eastern parts of the country were evaluated as potentially suitable for DGR (Fig. 1), which is because of the great depth of their occurrence (1500–2300 meters) in the Western part. Thickness is not an issue for this formation, only about 50 m thick weathered zone could be detected in the upper part. The density of crystalline rocks is high and reaches 2.8 Mg/m³. The most prospective rock types are represented by cratonic (anorogenic) granitoid intrusions forming rather large massifs in some places (Kapčiamiestis, Kabaliai). These rocks are least damaged by tectonic activity. Furthermore, lithology variations at short distances are minor, which makes exploration much easier. Yet, other rock types (gneisses, mafic intrusions, migmatites) form only weakly fractured blocks, which also may be prospective for a repository. Judging by very low seismic activity, southern Lithuania is affected by very low tectonic stress. The hydrogeological well tests indicate that tectonic zones are water-saturated, whereas homogeneous blocks are water-proof. Salinity of the formation water does not exceed 30 g/1 (except some rare anomalies), which is favourable for engineered barriers. The water flow field of the basement has not been well understood yet.

**Lower Cambrian clay.** The oldest part of Lower Cambrian–Baltija group – consists of the compact clay formation. This formation is located in Eastern Lithuania at a depth of 300–500 and more meters. Clay is very compact and consists of illite (from 60–65 to 85–90%), kaolinite (from 3–5 to 25–30%) and chlorite (from 3–5 to 10–15%) minerals. There are some interlayers of sandstone in Lower Cambrian clay. In the central part of the Lower Cambrian clayey formation distribution area, local sandstone lenses vary from 2 to 9 m in thickness, and two considerable sandstone layers in the lower portion of the section (10–16 m of thickness, increasing up to 25 m in the very frontier area in the East) could be traced all along the cross-sections. Sandstone interlayers are potentially highly permeable transport pathways; in such a

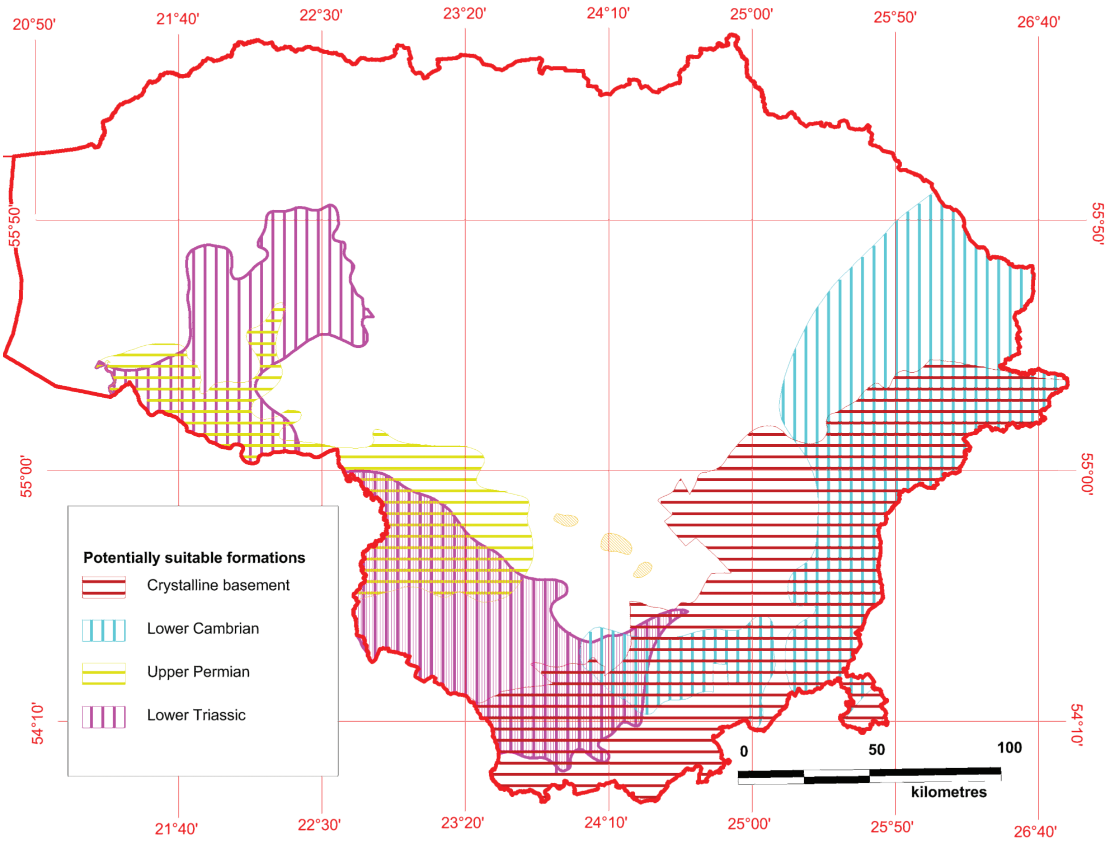


**Fig. 1** Potentially suitable geological formations for DGR in Lithuania (Kanopiene *et al.* 2005)

case the clay barrier thickness would be about 40 m. The Lower Cambrian Clayey Formation is rather poorly investigated, and only data on more than 100 wells are available. Sediments are also rather poorly studied in terms of mechanical properties, and only a few parameters are available (density of the rock equals to 2.22–2.25 g/cm$^3$, magnetic susceptibility is 0.08–0.14 $\gamma$*10$^{-3}$).

**Permian evaporites.** The entire layer of anhydrite, which is 40–60 m thick, occurs in the Southern and South-western part of Lithuania, in the area of more than 12 000 km$^2$. This layer lies at a depth of 150–790 m. The major part of these deposits (70–80%) consists of anhydrite. The 5–8 m thick layer of Permian gypsum occurs above the anhydrite layer, and the 3–5 m thick layer of gypsum lies below the layer of anhydrite. The exploration of anhydrite was carried out at the Pagiriai site in Kaunas district and its resources thereat were estimated at 81.5 million tons. The project for the exploitation of anhydrite applying underground mining was prepared. According to this project, the empty underground cavities remaining after the exploitation of anhydrite could be used for the DGR construction (Kadūnas 1993). On the other hand, such a concept should be ruled out because of the probable human intrusion in the future.

The Upper Permian rock-salt basin covers almost the whole Kaliningrad region (Russian Federation). Only the Northern edge of this basin is detected in the south-western part of Lithuania. This territory was investigated applying seismic methods. According to the obtained seismic data, salt is expected to occur in the form of single domes. The supposed salt bed was determined using electric log diagrams in oil prospecting boreholes. The prospecting and evaluation of the Usėnai rock-salt deposit was carried out in Šilute district. There were two deep boreholes drilled and rock was lifted in the Usėnai deposit. According to the drilling and seismic data, the area of the salt dome is 2.5 × 3.0 km. The evaluated thickness of the rock-salt in the central part of the deposit is 56.5–69–.0 m, and the implied thickness is about 75 m.

**Lower Triassic Clay.** The Lower Triassic deposits occur in the Western and South-western part of Lithuania at a depth of 250–350 m and are more than 200 m thick. In general, the sequence consists of dense clay. The most important compounds of the clay are the minerals of illite and smectite groups. There are many siltstone and some sandstone interlayers in the sequence of Lower Triassic deposits (Kanopienė, Marcinkevičius 2000). The void ratio of claystone is 0.299–0.565, the bulk density of the sediments varies from 1.96 to 2.29 Mg/m$^3$, the density of solid particles reaches up to 2.65–2.82 Mg/m$^3$. The index of plasticity of sediments exceeds 0.08 (reaching 0.12–0.29 for the most favourable layers). The maximal moisture content is within the range 11.2–15.8%, the natural moisture content – 0.1–0.178, and permeabi-

**Table 3** Matrix for the formation suitability calculation

| Geological factors | SR | Criterion and its number | W | Intervals of values or qualitative evaluations and suitability indexes | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | interval | SUI | interval | SUI | interval | SUI | interval | SUI | interval | SUI |
| Engineering geological conditions | 4 | 1. Depth, m | 0.2 | <200 | 0 | No data | 1 | >700 | 2 | 200–500 | 3 | 500–700 | 5 |
| | | 2. Formation thickness, m | 0.2 | <50 | 0 | No data | 1 | 50–70 | 2 | 70–100 | 3 | >100 | 5 |
| | | 3. Bulk density, Mg/m³ | 0.2 | <1.8 | 0 | No data | 1 | >2.6 | 2 | 1.8–2.2 | 3 | 2.2–2.6 | 5 |
| | | 4. Area of occurrence, km² | 0.1 | <10 | 0 | No data | 1 | 10–50 | 2 | 50–100 | 3 | >100.0 | 5 |
| Tectonic regime | 4 | 5. Velocity of vertical movement of the Earth crust, mm/year | 0.1 | >5.0 | 0 | No data | 1 | 3.0–5.0 | 2 | 1.0–3.0 | 3 | <1.0 | 5 |
| | | 6. Distance from the active fault, km | 0.05 | 0–5.0 | 0 | No data | 1 | 5.0–25.0 | 2 | 25.0–50.0 | 3 | >50.0 | 5 |
| | | 7. Probability of volcanic event, qualitative | 0.05 | high | 0 | No data | 1 | – | – | low | 3 | very low | 5 |
| Mineral resource exploration | 4 | 8. Distance from mineral resource site, km | 0.1 | 0–5.0 | 0 | No data | 1 | 5.0–25.0 | 2 | 25.0–50.0 | 3 | >50.0 | 5 |
| Hydraulic connection with human environment | 3 | 9. Low permeability sediments in formation cover, % | 0.25 | | | 0 - 10 | 1 | No data | 2 | 10–50 | 3 | >50 | 4 |
| | | 10. Presence of aquifers, number | 0.1 | | | >3 | 1 | No data | 2 | 1–3 | 3 | 0 | 4 |
| | | 11. Distance from palaeoincisions, km | 0.1 | | | 0–10 | 1 | No data | 2 | 10–30 | 3 | >30.0 | 4 |
| Movement of groundwater | 3 | 12. Formation permeability, m/s | 0.25 | | | $>10^{-4}$ | 1 | No data | 2 | $10^{-9}$–$10^{-4}$ | 3 | $<10^{-9}$ | 4 |
| | 3 | 13. Direction of vertical flow, qualitative | 0.2 | | | up | 1 | No data | 2 | down | 3 | equal level | 4 |
| Radionuclide transfer | 3 | 14. Salinity of groundwater, qualitative | 0.05 | | | unsaturated solution | 1 | No data | 2 | – | – | saturated solution | 4 |
| | | 15. Solubility of radionuclides, qualitative | 0.05 | | | high | 1 | No data | 2 | low | 3 | low | 4 |
| Uncertainties due to geological conditions | 2 | 16. Density of fractures, 1/m³ | 0.3 | | | >1 | 1 | No data | 2 | – | – | <1 | 3 |
| | | 17. Number of interlayers | 0.3 | | | >1 | 1 | No data | 2 | | | <3 | 3 |
| Uncertainties due to climate | 2 | 18. Probability of temperature changes, qualitative | 0.05 | | | high | 1 | No data | 2 | | | low | 3 |
| | | 19. Glaciation probability, qualitative | 0.05 | | | high | 1 | No data | 2 | | | low | 3 |
| Formation changes due to DGR impact | 2 | 20. Possibility of formation weakening, qualitative | 0.1 | | | possible | 1 | No data | 2 | | | no possibility | 3 |
| | | 21. Probability of fracturing | 0.2 | | | high | 1 | No data | 2 | | | low | 3 |
| Improvement of isolating properties | 1 | 22. Fracture self- sealing probability | 0.7 | | | No probability or no data | 1 | | | | | probable | 2 |
| | | 23. Presence of minerals of higher sorption capacity | 0.3 | | | No probability or no data | 1 | | | | | presented | 2 |

lity values vary from $10^{-11}$to $10^{-12}$ m/s (Kanopienė *et al*. 2005).

## Calculation of geological formation suitability

The first part of the final suitability evaluation matrix in the suggested methodology is devoted to the grouping of criteria according to the DGR performance scenarios (Table 3). The value of significance rank SR is assigned to each group. After grouping all the criteria, weighting of a single criterion within the group should be performed and the weighting value W should be determined. Then, quantitative values or qualitative evaluations of parameters characterizing the criteria should be analysed. Suitability indexes SUI should be assigned to the values of parameters or to the qualitative evaluations. Finally, the suitability score SS of the geological formation could be calculated according to the formula

$$SS = \sum_{i=1}^{n} SR_i \times W_i \times SUI_i ; \qquad (1)$$

where $i$ is the number of each criterion;
$n$ is the total quantity of the criteria evaluated.

The set of 23 geological criteria used in the matrix is not finite and amendments could be made if more investigation data are available. As an example of formula (1) application, the suitability score of the Lower Triassic clayey formation and that of the crystalline basement were calculated, using indexes presented in table 3 and all the data available on potentially suitable formations in Lithuania. The suitability score of the lower Triassic is 32.5 and that of the Crystalline basement is 26.35, which implies that the lower Triassic formation is more suitable for the DGR siting than the formation of crystalline basement.

## CONCLUSIONS

Methodology for selecting a geological formation for the DGR installation was prepared in accordance with IAEA safety requirements and recommendations. The proposed methodology is based on the principles of analytic hierarchy process and multi-criteria evaluation. A set of 23 geological criteria have been used to calculate the formation suitability for the DGR installation. The advantage of the discussed methodology is the possibility to use qualitative evaluations together with quantitative investigation results. If used in combination with GIS technology, this methodology can be applied for selecting not only a suitable geological formation but also a suitable site for the DGR installation. The scores of the formation suitability calculated employing the proposed methodology show that in Lithuania, the Lower Triassic formation is more suitable for the DGR system than that of the Crystalline basement.

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## REFERENCES

Ahlroth, S., Nilsson, M., Finnveden, G., Hjelm, O., Hochschorner, E. 2011. Weighting and valuation in selected environmental systems analysis tools – suggestions for further developments. *Journal of Cleaner Production 19* (*2–3*), 145–156, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2010.04.016, (https://www.sciencedirect.com/science/article/pii/S0959652610001678)

He, J., Zhou, Y.X., Zheng, G.S. 2020. Research on the geological suitability evaluation system of underground space resource utilization in Beijing. *Chinese Journal of Underground Space and Engineering 16 (04)*, 955–966.

Hoseini, Y., Kamrani, M. 2018. Using a fuzzy logic decision system to optimize the land suitability evaluation for a sprinkler irrigation method. *Outlook on agriculture* 298–307, https://doi.org/10.1177/0030727018798381

IAEA. 1981. Underground disposal of radioactive wastes. *Recommendations, basic guidance IAEA, Vienna*, *1981* (safety series No. 54).

IAEA. 1994. Siting of Geological Disposal Facilities, safety guide. *Vienna, International Atomic Energy Agency, 1994* (safety series No. 111-G-4.1).

IAEA. 2011. Geological disposal facilities for radioactive waste, specific safety guide. *Vienna, International Atomic Energy Agency*, *2011* (safety standards series, No. SSG-14).

Iwaro, J., Mwasha, A., Williams, R.G., Zico, R. 2014. An Integrated Criteria Weighting Framework for the sustainable performance assessment and design of building envelope. *Renewable and Sustainable Energy Reviews 29*, 417–434, ISSN 1364–0321, https://doi.org/10.1016/j.rser.2013.08.096, (https://www.sciencedirect.com/science/article/pii/S1364032113006369)

Kadūnas, V. 1993. Viršutiniojo permo anhidrito klodo ekogeologinis įvertinimas saugyklų įrengimo požiūriu [Environmental geological evaluation of upper Permian anhydrite from the repository construction point of view]. *Geologija* [*Geology*], *15*, ISSN 0202-327X [In Lithuanian].

Kanopienė, R., Marcinkevičius, V. 2000. Possibilities for developing deep radioactive waste repository in Lithuania. *Földtani Közlöny 130 (2)*, 251–261. Budapest, ISSN 0015-542X

Kanopienė, R, Šliaupa, S., Lazauskienė, J., Mažeika, J., Maselienė, V., Baliukevičius, A., Giedraitis, R., Satkūnas, J. (ed.). 2005. Investigations of Possibilities to Dispose of Spent Nuclear Fuel in Lithuania: a Model Case. *Geological Survey of Lithuania 1*, 66 pp. Suitability of Geological Environment in Lithuania for Disposal of Spent Nuclear Fuel. Institute of Geology and Geography. Vilnius, UDK 621.039.75: [55:551.242.03] (474.5)

Mallants, D., Suckow, A., Bertsch, P., Griffiths, H. 2018. Global Review of Site Suitability Conditions for the Geological Disposal of Radioactive Waste. In: *Waste Management 2018; 18–22 March 2018. Waste Management Symposia Inc., 2018, 14*. Phoenix, Arizona, http://hdl.handle.net/102.100.100/87179?index=1

Mendoza, G.A. 1997. Introduction to Analytic Hierarchy process: Theory and applications to Natural Resources, Management. In: *Proceedings of 1997 ACSM/ASPRS Annual Convention 4*, 130–39. *Resource Technology*. April 7–10. Seattle: WA.

Odu, G.O. 2019. Weighting Methods for Multi-Criteria Decision Making Technique. *Journal of applied sciences and environmental management 23* (*8*), 1449–1457, e ISSN: 2659–1502, print ISSN: 1119–8362, doi:10.4314/jasem.v23i8.7

Saaty, T.L. 1995. Decision making for leaders. The analytic hierarchy process for decisions in a complex world. *RWS Publication, PA*. 3rd edition.