EVOLUTION OF THE REPOSITORY IN THE NIZHNEKANSKIY MASSIF UNDER THE INFLUENCE OF CLIMATIC FACTORS

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Article received on September 25, 2020

The study identifies climatic factors related to external influences governing the long-term evolution of the RW disposal system at the Yeniseiskiy site. The paper evaluates the current state of knowledge about these factors and indicates most important research areas. These include: paleoclimatic studies in the repository region to clarify the climate history of past geological epochs; quantitative regional climate forecast based on global numerical climate models; special forecasts based on a general climate model of the region allowing, in particular, to clarify the depth of rock mass freezing during ice periods.

Keywords: *radioactive waste, evolution of deep geological repository, FEPs, paleoclimatic studies, long-term climate forecast.*

Introduction

Russian regulations and international recommendations indicate that predictive model calculations should be performed to assess the dose loads in the biosphere for a time-frame covering a period while the disposed radioactive waste (RW) potentially remains hazardous [1, 2]. No specific indications on relevant time periods are provided in these documents as regards deep disposal facilities for RW Class 1 and 2. However, based on the rate of their radioactivity decrease, one can estimate the latter as ranging from hundreds of thousands to millions of years.

The task associated with the identification of focus areas for further research based on which probable scenarios describing quite long-term evolution of a disposal system could be reliably forecasted is seen as an essential one for DDF RW safety case development. The so-called FEP concept (features, events, processes) summarizing numerous factors that can potentially affect the safety of a disposal system is used to provide full coverage of probable scenarios [3]. Events can influence features and processes, which, in turn, can influence each other. In some cases, a process can result in an event, for example, such processes as the accumulation of tectonic stresses in the bedrock or permafrost zone formation can result in some cracks or relevant changes, thus, affecting DDFRW safety. If these differences are not fundamental, the term "factor" or the FEP abbreviation is used.

This article follows up the study on the identification of FEPs being relevant for the DDFRW developed at the Yeniseiskiy site. The first part of this study [4] was devoted to geological factors, whereas this paper focuses on the climatic ones. The article is geared towards the specialists concerned with the topic of geological RW disposal drawing their attention to the fact that climatic aspects should

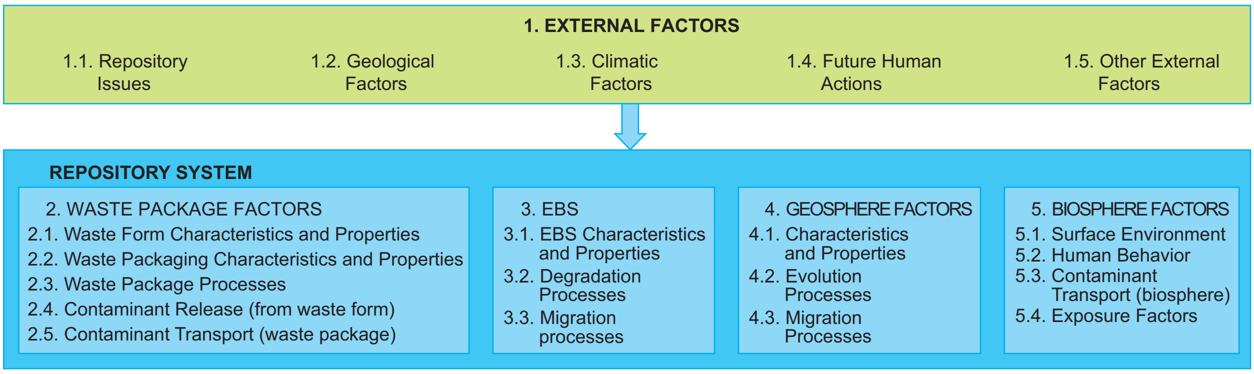

Figure 1. Layout of NEA OECD's FEPs catalogue

not be overlooked in the long-term safety assessment. This paper highlights the climatic factors that may prove to be important for the long-term DDF RW safety. The factors to be taken into account in DDF RW evolution scenarios should be identified, therefore the data on paleoclimatic conditions in the area should be available, as well as proper understanding of which climatic models may be required for their extrapolation to the distant future.

Features, events, processes (FEP) and their categorization

Starting from 1993, OECD NEA's Radioactive Waste Management Commission has been developing a generic international FEPs catalog. The latest (third) edition of this catalog was published in 2019 and includes 268 items [7]. This catalog is currently considered as the most complete one enabling to develop FEPs lists tailored for any specific disposal design (Figure 1).

The NEA OECD's catalog features factors affecting all subsystems of future repository: these take into account all possible interactions, direct links and feedback, thus, allowing to identify the FEPs being considered particularly important for particular disposal designs, for example, for the facility to be sited at the Yeniseiskiy site. According to the catalogue, FEPs are divided into 5 groups also involving some factors that are required to describe the evolutionary changes in migration model parameters.

FEPs have been evaluated in Russia as well. For example, IGEM RAS [6—8] and IBRAE RAS [9] did consider them in their research, including those performed under the DDFRW to be sited at the Yeniseiskiy site. This paper particularly addresses the subgroup of climatic FEPs (1.3) discussed under the group of External factors (No. 1). Climatic factors, in turn, are associated with factors from other groups and subgroups. In particular, they produce certain impact on migration processes in the geosphere and within the system of engineered safety barriers (EBS).

The list of external climatic FEP usually includes those that will manifest themselves mainly within the bedrocks enclosing the underground structure. In some cases, they can affect the internal EBS system (Table 1).

Table 1. Climatic EBS governing disposal system evolution (according to [5])

FEP ID number and name	
1. External Factors	
1.3.	Climatic factors
1.3.1	Global climate change
1.3.2	Regional and local climate change
1.3.3	Sea-level change
1.3.4	Periglacial effects
1.3.5	Glacial and ice-sheet effects
1.3.6	Warm climate effects (tropical and desert)
1.3.7:	Hydrological/hydrogeological response to climate change
1.3.8	Ecological response to climate change
1.3.9	Human response to climate change
1.3.10	Geomorphological response to climate changes

The initial task for any EBS assessment, including the climatic FEP, is seen in compiling an initial list covering the entire possible range of factors viewed as potentially relevant for the development of scenarios describing disposal system evolution. In our case, the NEA catalog was used to compile such a list [5]. Comparison of the initial list with the available information on the paleoclimates in the siting region allows to identify the FEPs list being considered relevant specifically for the DDFRW planned to be sited at the Yeniseiskiy site. This evaluation has resulted in a list of climatic FEP that should to be considered in the development of DDFRW evolution scenarios, as well as the tasks to be addressed during climatic FEP research.

In this paper, climatic FEP are characterized and analyzed in the order similar to the one indicated in the OECD NEA catalogue.

External climatic factors relevant for the Yeniseiskiy site (FEP 1.3)

1.3. Climatic factors

Climatic factors are associated with long-term processes resulting from global climatic changes and their impacts on repository performance and safety.

Climatic conditions are considered as a permanent feature of the external environment. A change in these conditions can initiate or affect the nature of many internal processes in the disposal system thereby the baseline scenario would be substituted by an alternative one. Due to the variety of possible climatic changes and the many elements of the disposal system that they can potentially affect, climatic factors are considered as most important in terms of the scenarios developed to describe the long-term DDF RW evolution.

In the disposal safety assessment, the following climatic influences [5] are considered:

1) intensity and nature of groundwater flows in the DDFRW near and far field;

2) chemical composition of groundwater in the DDFRW near and far field;

3) nature and spatial distribution of radionuclides released from the repository system.

1.3.1. Global climate change

This FEP considers possible future changes in the global climate and evidences of the past ones. This FEP deals with climate change-driven issues resulting from such global processes as variations in solar activity or anthropogenic CO_2 emissions. Climatic responses to geologic processes directly related to plate tectonics, such as volcanic activity or orogeny, are covered by FEP 1.2.14 (climatic responses to geologic change).

At present, the climate in the Northern Hemisphere is characterized as a relatively warm interglacial period, which should end with a new ice age in about 5 thousand years [10]. Possible sharp warming due to anthropogenic greenhouse gas emissions may introduce some changes to this global climate evolution scenario. At present, general atmospheric, ocean circulation and global climate models are being developed taking into account a variety of greenhouse gas input scenarios. These efforts allow to reproduce the main features of climatic system behavior, including climate evolution over the 20th century [11, 12]. Based on these evaluations, the limits of probable climate changes for the next hundreds of years may be assumed as reliable (within the framework of many scenarios). However, to evaluate the DDFRW safety, forecasts covering a much longer time-frame are required.

Global changes in climates of past epochs are seen as periodic in their nature having no exhaustive explanation. The hypothesis proposed by M. Milankovich [13] in the first half of the 20th century to explain the history of climatic changes in past geological epochs associated long-term climate fluctuations and the change of glacial and warm periods with changes in solar exposure. The intensity of the latter one is influenced by the changing inclination of the earth's axis with respect to the plane of its orbit, the precession of the earth's axis and the eccentricity of the earth's orbit. These parameters are changing within the time periods of some 40,000, 20,000 and 100,000 years respectively. Data from deep drillings of the ice sheet at the Russian Vostok station in Antarctica and later drillings in Greenland have confirmed the existence of periods similar to those mentioned above during the last 420,000 years. Milankovitch’s hypothesis explains not all the alternations of the Earth's climates, despite the fact that it is considered as the most long-range one in terms of climate forecasting for distant future. In addition to changes in solar exposure, quantitative calculations consider such factors as changes in the content of greenhouse gases in the Earth's atmosphere, shading of the surface due prolonged powerful volcanic eruptions or others depending on the model.

Under modern quantitative models, insolation is calculated based on the Milankovitch astronomical climate theory given the latitude of a particular territory and is summed up with different projections of anthropogenic CO_2 emissions and its long-term consequences [14]. Different projections of the future climates are obtained. Figure 2 presents a case study of various projections for the area of the Olkiluoto site in Finland.

According to model calculations, sustainable greenhouse gas emissions will postpone the next ice age beyond 120,000 years from now. At a low emission rate, the onset of the next glaciation depends on the insolation level and will probably occur in about 50,000—60,000 or 90,000—100,000 years from the present time (according to [14]).

It should be noted that the Olkiluoto latitude is 65 ° of north latitude and the latitude of the Yeniseiskiy site is 56 ° of north latitude. Accordingly, in these areas the level of insolation and, therefore, the distribution of warm and cold climate periods in time differs.

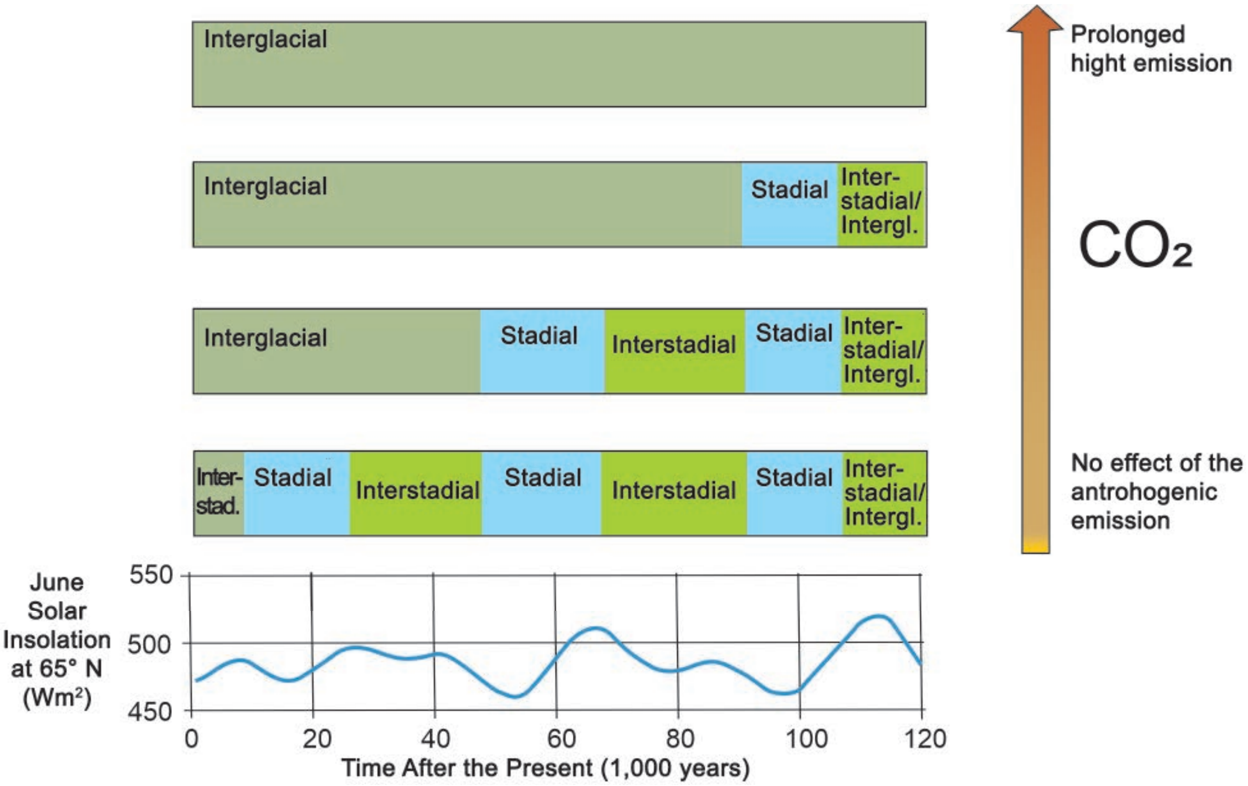

Figure 2. A schematic figure showing the role of solar insolation and atmospheric CO_2 concentration in terms of the next glacial inception

1.3.2. Regional and local climate change

This factor relates to possible future climate changes in the immediate vicinity of the DDFRW site and in a wider geographic region and relevant evidence of past climate changes.

FEP 1.3.2 differs from FEP 1.3.1 in a way similar to the one by which regional and local climatic changes differ from the global ones. Regional and local climate changes may affect the recharge regime and groundwater flow in the immediate vicinity of the repository and/or around it, which, in turn, will affect the radionuclide transport from the repository to groundwater discharge sites. Dietary changes can also impact the chemical conditions in and/or around the repository (for example, the influx of oxygenated meteoric water which will be able to seep deeper). Changes in temperature, amount and/or type of precipitation (e. g., rain or snow) can also affect the rate of erosion or accumulation of sedimentary rocks, which, in the long term, can cause a decrease/increase in the thickness of the repository overlying strata. Regional climatic features will also affect the processes of glaciation/deglaciation, watering/drying out of surface water bodies (for example, lakes). All these factors can potentially affect repository performance and safety, as well as the predictive dose calculations for the biosphere. Cooling/warming of the region's climate can cause the formation or thawing of permafrost accompanied by numerous processes in the near-surface zone. Humidification/desiccation (humidization/aridization) of regional climate impacts the groundwater level and the position of recharge and discharge areas, thus, in turn, affecting the evolution of the regional groundwater filtration field. Responses to regional climate change are discussed in FEP 1-3.4 — 1-3.10.

The duration and the scope of consequences associated with the future long-term (one hundred thousand years or more) climate changes in any region are modeled based on global climate projections. There are no quantitative local projections for the DDFRW area: this task should be addressed in the future. A number of studies [15, 16] involve qualitative forecasts showing the long-term evolution of the regional climate based on the extrapolation of the climates that existed in previous geological periods on the future perspective. Past regional climates of the Quaternary period were explored with a good agreement found between the course of warming and cooling stage alternations in general for the Northern Hemisphere. Published literature sources contain information required for a preliminary assessment of temperatures and other characteristics (precipitation, river runoff, vegetation) relevant for different climates that evolved in the past in the Yeniseiskiy DDFRW siting region.

In general, for the last 400,000 years the climates in this area were much colder than today's "moderately cold" climate: the only exception accounts for the periods of interglacial optima, when the climate was similar to the modern one or even somewhat warmer. Extrapolation of paleoconditions to the future can be considered as climatic analogies for probable scenarios of local climate change with or without an account taken of global greenhouse gas emissions (see FEP 1.3.5 and 1.3.6 discussed below).

1.3.3. Sea-level change

This FEP focuses on the evolution of sea-level fluctuations potentially resulting from the changes in the global climate and/or regional geological movements, such as isostatic uplift or subsidence of the earth's crust due to the emergence or removal of ice sheet loads.

Sea-level changes can inherently affect the safety of a repository sited close enough to a coastline that has been or is potentially subject to a heavy ice sheet cover. Periodic change in the groundwater supply from seawater to continental inevitably leads to a change in hydrogeochemical and hydrodynamic conditions and impedes predictive geomigration calculations. This situation is typical for the SNF repository in Sweden sited on the Scandinavian shield off the coast of the Baltic Sea [17].

As for the Yeniseiskiy site, firstly, it is sited more than two thousand kilometers south of the Kara Sea at an elevation of about 400 m above the sea level, and secondly, as it will be mentioned in FEP 1.3.5, throughout the Quaternary period it has never been covered by an ice sheet. It seems reasonable to assume that no expected climate changes can significantly affect its position. Accordingly, any significant effect of sea level fluctuations on the hydrosphere conditions and, consequently, on the disposal safety can be excluded.

1.3.4. Periglacial effects

This factor takes into account physical processes and associated landforms in cold but ice-free environments within the repository siting region/site. The subsurface conditions and geothermal gradient in the rocks of such areas will be also affected by the lack of the insulating effect produced by the ice sheet. A key feature of such environments is seen in the formation of large permafrost soil and rock volumes commonly referred to as “permafrost”.

Periglacial effects can affect repository performance and safety by influencing the phase state of water in the bedrocks, the nature of groundwater flows and the associated radionuclide migration processes. The permafrost zone can restrict groundwater recharge and the spatial distribution of ice, tabetisol and cryopegs can also affect the position of groundwater recharge and discharge areas. The hydraulic permeability of permafrost is several orders of magnitude lower than the common one and the infiltration through them is quite minor, whereas the level of uncertainty in the forecast of underground flows throughout the glacial cycle is considered as quite high [18]. Partial freezing of the environment can lead to the development of higher residual salinity of groundwater (cryopegs are usually represented by saline waters). Freezing-thawing processes with periodic changes in the global climate can lead to the development of ice wedges, thermokarst processes, solifluction and other distinctive forms of landscapes in periglacial areas. Spatial distribution of permafrost will change with the advance and retreat of adjacent ice sheets. These processes will cause changes in drainage systems affecting the near-surface groundwater flows and also causing changes in plant, animal and human communities that will in turn affect potential radioactive effects in the biosphere.

By present time, only some rare thin permafrost islands remain in the region [19, 20]. Permafrost was not found directly in the repository area. Due to the bare surface of the earth during Quaternary glaciation periods, a very thick (up to 600 m) stratum of permafrost evolved on this territory [21], thus, similar effect can be expected during future glacial climates. The analogy drawn to the three European repositories (Czech Republic, UK and Sweden) in assessing the thickness of the permafrost zone in the coming ice age, as shown in [16], is believed to be incorrect. Authors of this study do not take into account the known asymmetry in the ice sheets developed between Europe-America and Siberia [21, 22] and, accordingly, the different permafrost depths in these regions. In Europe-America, glaciers have penetrated further south, while frozen rocks, on the contrary, did intrude deeper in the south of Siberia. According to the selected analogs, in European territories, freezing to a depth of over 320 m is not expected under a thick ice sheet.

Considering the Yeniseiskiy siting conditions with the permafrost depth that did exceed the disposal one during the last glaciation, the case of complete EBS freezing cannot be ruled out [15]. This can ambiguously impact the EBS system and to mitigate relevant consequences some special experiments would be required. Iron hydroxides found in a number of cracks up to a depth of over 500 m can be viewed as indirect evidence of repeated freezing and thawing processes that have occurred in the rocks of the Yeniseiskiy site. Until quantitative calculations are completed, complete EBS freezing scenario can be considered as highly probable. Only future local climate modeling can provide an ultimate answer to the question regarding the inherent influences in the periglacial region.

1.3.5. Glacial and ice-sheet effects

This FEP describes and evaluates the role of glacial climate and ice sheets within the DDFRW region/site, for example, as regards the changes in the geomorphology, erosion rates, mechanical and hydrodynamic characteristics.

Reconstructions of the last (Sartan) glaciation can be used as a paleo-analog for the glacial climate in this region. The phase of the Sartan glaciation began around 25,000 — 23,000 years BC. The maximum cooling level in the Western Siberia was attained some 20,000 — 18,000 years ago. Data on regional historical temperatures for this glacial stage are not available. During the earlier Shaitan glaciation, local July temperatures were 4 — 6 °C lower than nowadays, January temperatures dropped to −29 °C (ΔT −8 °C) and the average annual temperature was 7 — 8 °C lower than the present one [21]. According to [23], in the south of Eastern Siberia, relative to the present level the decrease in the average annual temperature for the Sartan climate was found to be ranging from 6 to 9 °C with the decrease in the annual precipitation ranging from 200 to 450 mm.

Ice sheet development starts with the onset of a glacial climate. Presence or absence of glaciers affects groundwater recharge and headwaters. Head gradients tend to increase in the vicinity of ice sheet edges, which also affects the geothermal gradient in the below rocks due to thermal isolation provided by the ice. Massive ice sheets can cause earth's surface depression. After glacier retreat, the earth's surface starts to restore its former position. Erosion processes associated with the glaciers (gouging) and melt water flow can cause morphological changes in landscapes and, consequently, affect groundwater hydrodynamics.

As for the Yeniseiskiy site, available data shows that over the last four global glaciations of the Northern Hemisphere in the Quaternary geological period, it has never been covered by an ice sheet which is explained by some regional features of atmospheric circulation, which were formed due to the uplift of the Altai and Sayan mountain ranges south of the Yeniseisky site region during the Neogene-Quaternary time [10]. During the most large-scale glaciation (about 70,000 — 60,000 years ago), the ice cover has moved southwards along the river Yenisei only up to 64° of northern latitude. The northern boundary of the Nizhnekansk massif is located 830 km southward [21]. The boundary of the latest ice sheet was located north of the Yenisei Ridge in the Podkamennaya Tunguska area [24]. Accordingly, in the DDFRW safety assessment similar future glaciation scenario assuming the influence of factors associated with ice sheet formation and melting can be excluded from consideration.

1.3.6. Warm climate effects (tropical and desert)

This FEP deals with the effects of tropical and desert climates, including seasonal, meteorological and geomorphological effects inherent in these climates. Under DDFRW safety assessment, this factor can be considered only as a possible consequence of global warming associated with the emission of greenhouse gases.

Climate warming can indirectly enhance the role of humidification or desiccation. Increased precipitation (humidization) increases groundwater recharge and accelerates water exchange. On the contrary, water exchange is slowed down by desiccation. In any case, hydraulic processes in the geosphere will evolve.

In the biosphere, these effects can include extreme weather conditions, for example: monsoons, hurricanes in tropical climates; in desert climates, these impacts also include desertification, which can lead to deforestation and loss of forests and pastures with corresponding implications for the dose calculations.

Warm climate can have a profound effect on the groundwater level: in tropical regions it is usually close to the earth's surface, but can correspond to a considerable depth in arid regions (aeration zones with a capacity of hundreds of meters are known). Such groundwater level lowering potentially affects natural biota and impedes public water supply.

In the event of a global warming , possible scope of climate change in the Yeniseiskiy siting area can be judged based on paleoclimate data. The climate of the last interglacial period (130,000 — 115,000 years ago), known in Siberia as Kazantsev (Mikulinsk — in Eastern Europe), corresponds to a relatively small excess of average annual temperatures over the modern ones (by about 2 °C) [15, 16]. Over the next century, this predicted rise in global temperatures is assumed to be due to the greenhouse effect. According to the reconstructions presented in [21, 25], the average January temperatures in the region of the Krasnoyarsk city in Kazantsevo time exceeded the modern ones by 6 °C, whereas, on the contrary, the July temperatures were almost the same. The Krasnoyarsk region was located in the zone where the annual precipitation level was 100 mm higher than the present one. The river runoff in the Krasnoyarsk region also exceeded the current values by no more than 50 mm. The Tobolsk interglacial period (380,000 — 270,000 years ago) is considered as the warmest period in the regional history: it was one of the longest interglacial periods, and in the future, similar situation may arise with a very strong greenhouse warming of the atmosphere due to uncontrolled greenhouse emissions. Average annual temperatures were 10 °C higher than the modern ones. The winter season was shorter and warmer than now by almost 7 — 9 °C; the summers were longer, more humid and moderately warm.

Interesting is the data on the rate of changes in the glacial conditions to the interglacial ones. With the warming started in late Sartan glacier period, which reached its maximum some 20,000 — 18,000 years BC, the permafrost degradation process was launched. In a short period (about 13,000 to 10,000 years ago), the southern boundary of the Western Siberian continuous permafrost zone retreated to the latitude of the Arctic Circle at an average speed of about 400 km per century. Such rapid permafrost retreat has contributed to intensive melting of underground ice, development of thermokarst processes and noticeable deformations of the earth's surface, including erosion processes in watersheds and river valleys [21]. These data can serve a basis for a hypothetical scenario. If complete EBS freezing occurs, radionuclide migration will tend to be diffusional in its nature; over some tens of thousands of years of the ice age, a significant radionuclide inventory will be accumulated in the near zone, which, along with a rapid thawing, will almost simultaneously enter the underground hydrosphere. This effect can dramatically increase the dose loads on the biosphere.

1.3.7. Hydrological/hydrogeological response to climate change

This factor considers changes in the hydrology and hydrogeology of the DDFRW siting region/area, for example, surface and groundwater recharge, precipitation, its type (rain, snow) and seasonality, in response to a climate change. In the long term, climatic changes may result in salinization (desalination) of groundwater due to changed intensity of its recharge. Changes in groundwater chemistry affect the dispersion of radionuclides in the geosphere. Climate evolution will cause potential effects such as formation /disappearance of lakes and rivers, sedimentation and meander formation, waterlogging or desiccation of low-lying areas. Hydrological responses to climate change can also cause changes in the environment, in the nature and spatial distribution of ecosystems, which can be affected by radionuclides released from the repository.

Possible scale of climate humidization in the Yeniseiskiy siting area was modeled showing that this FEP has a low degree of impact on the radionuclide migration [26].

Formation of dammed lakes may be seen as an indirect consequence of ice sheet formation north of the future DDF RW site as was the case during previous glacial epochs [20]. In terms of the hydrogeological impact, formation of such lakes is equivalent to a decrease in the vertical differentiation of the groundwater level over the area. Simulations show that the impact of such an event on the scale of radionuclide migration can be assessed as low [26].

1.3.8. Ecological response to climate change

This factor is focused on changes in ecology, for example, vegetation or animal populations, in response to climate change within the DDF RW siting region/area.

Ecological responses to climate changes are essential for the safety assessment, primary since we have to understand what exactly are the natural objects (water, soil, flora and fauna) that may be affected by the repository.

Since no numerical models of the local climate are available for the Yeniseiskiy siting area, it is obviously premature to speak about the nature of future ecological changes.

1.3.9. Human response to climate change

This FEP focuses on changes in human behavior, such as habits, diet, community size, housing types, agriculture and settlement, in response to climate change in the DDFRW siting region/area.

This factor should be considered since, on the one hand, changes in geological and hydrogeological conditions, as well as in EBS system properties due to the impact of unfavorable climatic conditions can cause certain redistribution of dose loads on the population estimated under the baseline scenario. Human responses to climate change are related to repository safety since they determine: 1) the probability to which humans or other potential recipients will be exposed to radionuclides that can escape the repository system in the future; 2) toxicity of radionuclides to humans or other potential recipients; 3) duration of such exposure, if any.

On the other hand, changes in human behavior due to climate change can trigger anthropogenic impacts on the disposal system. People will respond to changes in the redistribution of safe natural resources, agricultural land and water resources (both surface and underground) in the ways available to them by changing their common way of life.

Since no numerical models of the local climate are available for the Yeniseiskiy siting area, it is obviously premature to speak about the nature of future human response to climate change.

1.3.10. Geomorphological response to climate change

This FEP takes into account the geomorphological response (landscape evolution) within the DDFRW siting region/area caused by climate change. Geomorphological responses to climate change occur over time, reflecting, for example, long-term changes in the average annual precipitation level. In some cases, responses can occur quickly, for example, in case of landslides. In turn, geomorphological responses can affect hydrological and ecological conditions. Landscape evolution will be accompanied by erosion, material transfer and deposition, which in general can affect the thickness of the repository overlying strata and, therefore, affect the space between it and the biosphere. Based on the available estimates rock denudation rate in the region over the past geological epochs, changes in the landscapes of the Yeniseiskiy site are likely to be minimal. More significant may be the changes in the ecosystem and biosphere, which are associated with the relief. Flora and fauna will be influenced by such factors as position in the landscape, proximity to surface water bodies, rivers or coastlines. All these factors will affect the concentration or dispersion of radionuclides escaping the repository and reaching the biosphere.

Conclusions

Climatic factors viewed as important external influences governing the long-term evolution of RW disposal system in the Yeniseiskiy siting region/area have been studied in the most general way.

Available data on regional paleoclimates are fragmentary in their nature providing only a rough estimate of future biosphere and geosphere conditions at the Yeniseiskiy site that will evolve under one of the assumed global climate change scenarios. To compile a list of scenarios for DDFRW safety assessment purposes, robust estimates of the times assumed as the onsets of climatic periods potentially impacting the dietary habits of the population (for example, a warmer climate or a colder, in fact, glacial climate) are required.

No numerical models of regional climate evolution for the time periods covering a timeframe of tens to hundreds of thousands of years are available, thus, rendering impossible rational assessments of many possible responses to global climate change in the disposal system and reliable forecasts of dose loads for future generations. The climate forecasting time-frame should cover a time period of over 10,000 years. At least, one should be able to track a complete climatic cycle starting from the current relatively warm state, i.e., at least 100,000-120,000 years ahead.

The most important areas of research on climatic factors are believed to be as follows:

- paleoclimatic studies in the DDFRW region to clarify the climate history of past geological epochs;
- quantitative regional climate forecast based on global numerical climate models;
- purposely tailored forecasts presenting geosphere and biosphere evolution based on the general regional climatic model, in particular, to specify the freezing depth of the rock mass during the ice ages. To assess the reliability of engineered barriers, as well as the probability of changes in the existing cracks and the formation of new ones, one should have precise knowledge on whether the bedrock is going to freeze to a depth of over 500 m (and when).

Acknowledgements

The study was partially funded under IGEM RAS's state assignment (research topic 0136-2019-0004).

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Bibiliographic description

Kochkin B. T., Bogatov S. A., Saveleva E. A. Evolution of the Repository in Nizhnekanskiy Massif under the Influence of Climatic Factors. *Radioactive Waste,* 2021, no. 1 (14), pp. 63—75. DOI: 10.25283/2587-9707-2021-1-63-75. (In Russian).