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EVOLUTION OF THE SAFETY CASE FOR LIQUID RADIOACTIVE WASTE GEOLOGICAL REPOSITORIES

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The paper considers the steps taken to upgrade the safety case of liquid radioactive waste geological repositories (LRWGR) with due account of relevant international standards. The discussed activities are based on analytical and experimental studies aimed at reducing the uncertainties of input data used in LRWGR models, increasing the quality of scenarios of LRWGR evolution, and development of the concept of LRWGR closure in accordance with the requirements of the in-force regulatory documents.

Keywords: *LRWGR, long-term safety, safety case, LRWGR closure, IAEA, standards.*

The idea of disposing of liquid radioactive waste (LRW) by their injection through the injection boreholes to deep geological layers was formulated at the end of 1950-s [1]. The main features of this disposal technology are specific requirements to permeability, rate of underground waters flow, capacity properties, etc. The host layer should be reliably isolated from the surface by thick layers of impermeable for the waste aquitard clays, as well as by one or more buffer aquifers. A series of surveys preceded the selection of sites for LRWGR. These surveys were to identify the properties listed above, which supported the acceptability of geological and hydrogeological characteristics of the relevant mining allotments for disposal of LRW with a given chemical and radionuclide composition [1].

There are currently three sites used for LRW disposal in the Russian Federation:

The test area “Site 18 and 18a” is located in the Northern section of the site of JSC “SCC”, State Corporation “Rosatom”, at a distance of 8.8 km from the residential area of Seversk in the Tomsk Region on the right bank of the Tom River. Here, the rocks of Paleosoic foundations are covered by masses of sand-clay Meso-Kainosoic rocks, which have sandy layers with collector properties and layers of clay aquitards. The thickness of sediments mass is 350 — 450 m.

- “Severny” site is located within the control area of FSUE FNO “MCC” of the State Corporation “Rosatom” on the right bank of the Enisey and B. Tel Rivers in 18 km to the South-West of Zheleznogorsk and in approximately 55 km to the North-East of Krasnoyarsk. LRWGR is located within the ancient erosion depression filled by a mass of interchanging sand and clay Jurassic sediments with a maximum depth of 550 m from the surface. From the West, the depression is limited by tectonic disturbance of sub-meridional distance, which has clay surface and isolates the underground waters of the depressed section from the upper mass connected with the Enisey River.

- "Trial and industrial site" is situated in the medium flow of the Volga River at 8 km to the West of Dimitrovgrad in the territory of the Centre of research installations of NIIAR, close to the radioactive waste management facility. There are 7 aquifer systems containing both fresh and mineralized waters, including salines, and layers of rocks having aquitard properties in the geological cross-section of the site. The properties of underground waters are characterized by a vertical hydrochemical zonality. The thickness of sediment mass is up to 2300 m. Permeable layers at the depth intervals of 1440—1550 and 1130—1410 m are used for LRW disposal.

In process of intense LRWGR operation, special attention was given mainly to operational safety, including monitoring of process parameters, personnel exposure, environmental parameters, identification and correction of deviations.

Consideration of long-term radiation and environmental safety was limited to monitoring of the contamination propagation plume and a number of studies of impact of disposal on subsoil. This information was included in annual safety reports submitted to the state nuclear management and regulatory bodies. Systematic information was also presented as the safety case report (SCR) and geological and hydrogeological justification of the extension of the operational period required to acquire operational and subsoil use licenses, respectively.

The long-term safety case at the design stage included analytical studies of migration of LRW components in underground waters for time periods within several hundreds and thousands of years. Subsequently, as monitoring information was accumulated, the better understanding of the characteristics of geological environment and migration parameters of LRW were used in repeated forecast calculations, first analogue and, later, digital.

In the last decade, the requirements to safety case of RW disposal facilities became stronger, taking into account the increase of scientific knowledge in the field of human and environment safety. One of the causes may be the upgrade of the regulatory framework: the Federal law "On the management of radioactive waste and on amendment of specific legal acts of the Russian Federation" of 11.07.2011 No. 170-FZ was enacted, as well as a series of federal regulations.

The main problem for justification of compliance of the LRW injection technology to the international standards [2—5] is related to its basic concept — disposal of waste in the liquid phase (without solidification) and the absence of engineered barrier system in the generally accepted sense, which is viewed by foreign specialists as a violation of the defense-in-depth principle. Though, it can be stated that defense-in-depth elements are present in the conception of LRWGR in the form of inter-changing aquitards and buffer aquifers.

The presence of such fundamental differences in interpretation of basic requirements was one of the arguments for the conduct of the IAEA peer review in 2013. The peer review was aimed at assessing the compliance of Russian approaches and procedures to long-term safety case of LRWGR to international standards. International experts reviewed the long-term safety case for a deep liquid radioactive waste disposal facility, which was based on documents submitted by Russian specialists as a part of license renewal process for the site "Severny" of Zheleznogorsk subsidiary of FSUE "NO RW".

The comments of the experts in essence covered the following issues: (1) absence of the systematic character of LRWGR description, which complicates justification of completeness of account of safety-relevant factors; (2) insufficient level of scientific arguments to support the fundamental safety functions assurance in the long term, leading to utilization of conservative assumptions as a general ap proach throughout the safety case; (3) lack of ac count for various uncertainties. It should be noted right away, that essentially similar comments were formulated by Russian regulatory bodies in the license conditions. Relevant activities were organized, but did not provide exhaustive answers to the issues raised. Analysis of expert recommendations and formulation of research directions in response to these recommendations had formed the basis of the "Program of computational and experimental research for safety case and safety assessment of the liquid radioactive waste geological repositories", which was approved by the State Corporation "Rosatom" and Rostechnadzor in 2015. Scientific foundations for formulation of research directions in the Program are given in [6].

The mainstream trend of the last years is minimization of LRW generation and development of technologies for its solidification. Concepts of LRWGR closure complying with the in-force regulations and the available level of knowledge will be completed before the end of the operational period of these facilities, along with the closure programs and relevant design documentation. In the general case, closure shall include dismantlement of surface installations, closure of part of boreholes, modernization of the remaining boreholes and drilling new ones for monitoring purposes and or-ganization of monitoring of the disposal system and environment conditions. The duration of in- stitutional control measures, including monitoring of geosphere and biosphere, and limit of access to the site, would be justified in the Closure documentation.

Fundamentals of the current approach to long-term safety case

International experience and IAEA documents suggest that safety case shall be interpreted as a collection of arguments and evidence in support of the safety of a specific facility or activity [2]. The safety case contents are upgraded in a stepwise procedure of facility development and accumulation of information. Thus, the structure of the final safety case document for a certain stage of the lifecycle, or for LRWGR, for facility closure, is a description of the main aspects assuring the safety of the RW disposal system with references to documents containing detailed description of studies, models, calculations and conclusions relevant to these aspects. Such a structure provides, on one hand, a manageable scope of the final documents, and, on the other hand, use of all the available information.

As the documentation for all LRWGR was inconsistent, a decision was made to standardize the works on safety cases for all facilities and development of relevant documents in order to assure the systematic character of description of the systems and their elements, account for all safety-relevant factors and various uncertainties, quality assuarance, etc. The developed stepwise methodology is described in detail in [8].

In accordance with the developed methodology, a series of reports needs to be prepared that shall make reference to reports on specific studies and research works.

“Report on the data” is the result of acquisition, analysis and systemization of all accumulated information on the conditions at the LRWGR site, including regional characteristics (geographical, meteorological and geological), site characteristics (geological and hydrogeological conditions, physical-chemical composition of rocks and ground water), process characteristics of RW disposal system (location of system elements, materials and properties of surface and underground structures, volumes of LRW disposed via specific boreholes), LRW characteristics (radionuclide and chemical composition, chemical and physical properties), results of consequences simulation performed at all stages from design development to latest calculations. An important aspect of this work is to identify and categorize all types of uncertainties and proposals for their reduction. 4 types of uncertainty groups were identified: geological, related to impossibility of obtaining complete information on inhomogenities of geological environment; process, associated with insufficient knowledge of man-caused transformations of geologic environment in the process of interaction with LRW components; scenario, associated with low forecasting capabilities for external processes; parametric that are related to the methods for selection of parameters for mathematical modeling. Understanding of the sources of some uncertainties resulted in selection of such research directions as improvement of geological models, carrying out additional studies and improvement of methods for simulation of the processes of interaction between LRW components and geological environment, formulation of scenarios for events that are difficult to forecast.

The “Geology report” shall include all available information characterizing the geology of the regions and sites of LRWGR, including historical summary of studies of the geological environment, detailed description of stratification and lithology, seismic and hydrogeological conditions. Special attention shall be given to the characteristics of geological environment having the highest effect on the process of LRW components transport and the extent of knowledge of these processes. Geological evolution of the regions of LRWGR location needs to be described to provide the scenarios of geological evolution both for the existing tectonic disturbances and for seismic activity and the potential appearance of new disturbances.

The history of formation of geological conditions at the sites of facilities supposes that abrupt endogenic or exogenic geological processes have a low probability for the period of up to 100 000 years.

The “Climate report” contains the forecasts of main climatic parameters (temperature and precipitation) for the period of up to 100 000 years, based on the joint of the projected trends of natural climate evolution and anthropogenic impact for the regions of LRWGR location — Zheleznogorsk (Krasnoyarsk Krai), Seversk (Tomsk Region), and Dimitrovgrad (Ulyanovsk Region). These studies show that anthropogenic component would be negligible for the time interval of over 1000 years. Natural trends of climatic parameters have been assessed based on the analysis of available paleogeographic and paleo-climatic data. Most probable scenarios of climate evolution for the regions of LRWGR location have been developed. The scenarios do not forecast glaciation of the regions in future ice ages, but do suggest the possibility of depletion of the upper aquifers (example of precipitation projection for 10000 years for LRWGR “Seversky” is given in fig. 1).

Reports on FEP (feature, event, and process), evolution and processes are strongly interconnected and have a common objective — to assure account for all factors affecting the safety of RW management system.

FEP is a single factor: feature, event or process. Feature — object, structure or condition, which may potentially affect the disposal system. The feature is described by a qualitative or quantitative value, including a list or a relation, which may have a known or unknown level of uncertainty. Event is a natural or anthropogenic phenomenon, which is short in time compared to the system lifetime and has the potential to affect the evolution of the disposal system. Specific events trigger certain scenarios.

Process is a natural or anthropogenic phenomenon that might affect the evolution of the disposal system and that exists for substantial time period of facility operation.

Complete list of FEPs potentially connected with long-term existence and evolution of such types of disposal facilities is drawn up to understand the system. A set of most significant FEP is selected among all FEPs identified, and is used to determine the range of possible end conditions (evolution scenarios) for the disposal system. Scenario is a defined series of FEPs leading to potential future conditions of the system. The sequence may be undisturbed (normal evolution) or disturbed by a certain destructive event.

The full set of scenarios represents the whole range of possible future states based on the complete FEPs list.

Thus, the "FEP Report" represents the analysis of the whole internationally accepted list [7] of FEPs based on their significance for the LRWGR in general and for each site in particular. The "Processes report" studies the "process" type factors in more detail to be used for development of mathematical models. "Evolution report" is a number of considered scenarios taking into account the change of RW disposal system parameters.

Evolution of models and computational research

Long term safety case for LRWGR cannot be completed without model calculations because of the duration of the potential hazard period for disposed waste. Modeling simulates the processes actually taking place in the disposal system. The most significant processes involve filtration and migration of components in geological environment. Software code GeRa [10] is specially designed to simulate such processes and includes (1) account for such features as impact of surface geology and change of hydrological modes, thus providing calculations for various scenarios of climatic evolution of the region, as well as accounting for some aspects of anthropogenic activity; (2) account for effects of fast channels and other disturbances of geological environment; this is useful for calculation of various scenarios of geologic evolution and external impacts causing such disturbances; (3) account for chemical processes, thus providing assessment of radionuclide retention based on characteristic processes.

The safety analysis of the disposal system involved a number of studies simulating vertical flows between layers, e.g. along the borehole shaft or through the disturbances of aquitards. The presence of spatial areas with pressure gradients promoting vertical flows was being assessed, along with the impact of packing failures in boreholes and aquitards on vertical migration. The calculations demonstrated that vertical flows higher than the II aquifer are not characteristic for the hydrogeological system of LRWGR "Severny".

Fig.2 shows an example of upward movement of liquid along the failed borehole.

Approximately in 2700 years, the non-adsorbed components of the solution will reach 15 m from their initial level, which is insignificant for the buffer layers with the thickness above 150 m.

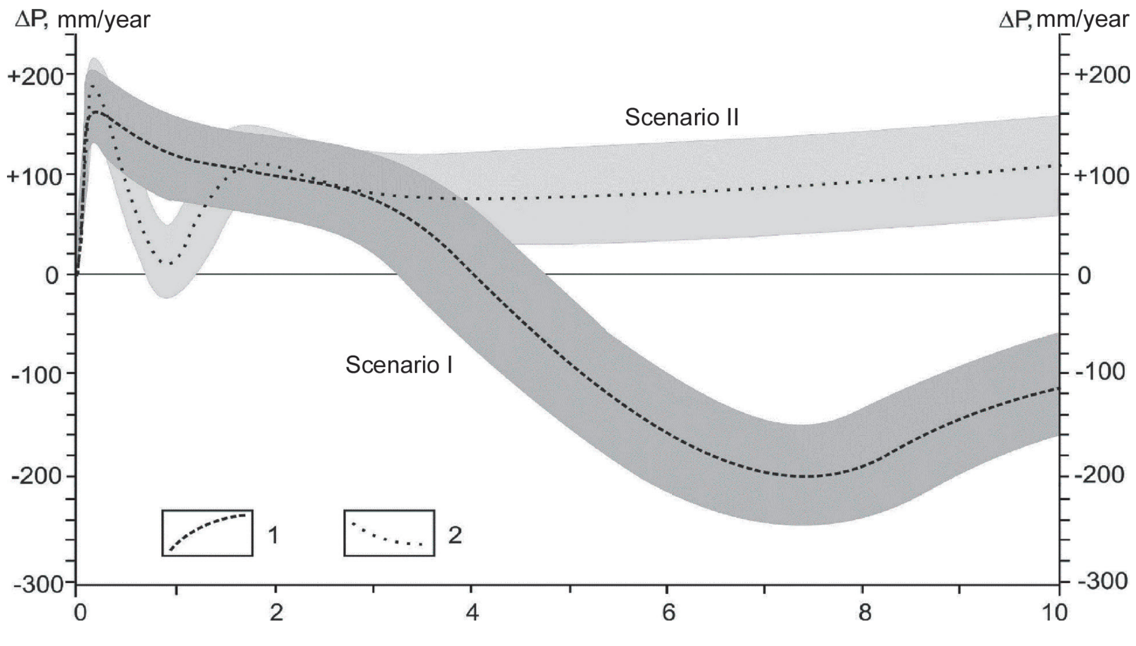

Fig. 1. Potential changes of the average annual precipitation amount in the vicinity of LRWGR "Seversky" (relative to the current value). Scenario I - stop of anthropogenic warming and return to the natural cooling trend; II - further warming due to greenhouse effect

The computation code used for the forecast calculations shall be calibrated for the actual conditions of LRWGR, i.e. there should be a parametric model of a specific facility. Special model GEOPOLIS [11] was developed for the "Severny" site, and is currently being certified by the expert council of Rostechnadzor of Russia. Calibration of the model defines the model limits and boundary conditions, geological model (structural and petrophysical characteristics with non-uniformities) [12], hydrogeological characteristics, geochemical model for justification of adsorption characteristics.

It is absolutely evident that the calculation assessments are subject to the effect of uncertainties, even if the scenario component is eliminated. Uncertainties caused by direct measurement errors and errors due to indirect assessment inaccuracies, use of mathematical approximations in simulation of processes, inaccuracy of characteristics of materials and their spatial distributions all have major effect on the results of model calculations.

It is impossible to completely eliminate the uncertainties. Therefore, a method of one-through analysis of uncertainty of the output relative to the level of uncertainty of the actually measured data was developed. The method takes into account the stepwise modeling process. This approach is demonstrated for geomigration modeling in the conditions of uncertainty of model parameters [9].

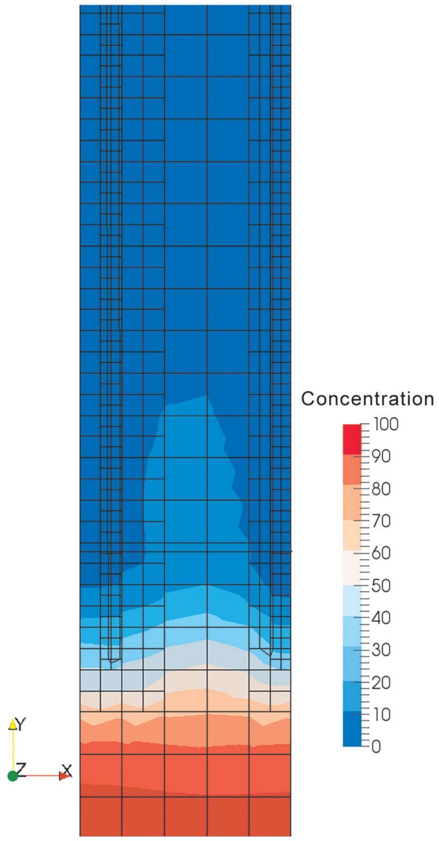

Fig. 2. Fragment of concentration distribution in case of a failure of a well with a potential of a vertical flow for time moment of 2700 years

Large scale experimental studies

The following studies need to be completed in order to improve the quality of parametrization of the LRWGR model and soundly justify the concept of LRWGR closure: degradation of borehole structural materials (metal, concrete) in the conditions of LRWGR, change of LRWGR characteristics over the operation period, impact of microbiological communities (if present) on the processes within LRWGR, generation of colloids and colloid transport. Detailed programs of these studies were formulated.

In-situ studies on additional research of the site were completed at the "Severny" site. They included geodynamic and seismic observations, as well as hydrogeological investigations at the area of Pravoberezhny tectonic disturbance (PTD).

Geodynamic and seismic observations were carried out using surface geodesic measurements, satellite methods, and seismological observations across a low aperture network. The observations and subsequent calculations demonstrated that there were no active tectonic disturbances at the "Severny" site of LRWGR.

Hydrogeological investigations involved monitoring of underground waters and identification of the relation of water levels in boreholes with atmospheric pressure, moon tides, geodynamic processes. The investigations carried out demonstrated that the level of underground waters of the elevated block and the third ("buffer") aquifer at the depressed block had natural undisturbed character. The main factor affecting the local level changes (within hours and days) and trends (within weeks and months) was the atmospheric pressure. No impact of long-term injection of LRW to the first and second aquifers on the third ("buffer") aquifer of the depressed block and the elevated block has been identified in the observations.

Another area of hydrogeological investigations was implementation of withdrawal of water from 4 sets of boreholes applying hydraulic sounding of the PTD area at the section between the relief circuit of the second aquifer and the location of observation wells of the elevated block.

The results of withdrawal did not show the presence of hydraulic connection between the aquifers located at the east and west sides of PTD.

Problem of LRWGR closure

The concept of LRWGR closure shall be formulated at the stage of its design in accordance with IAEA requirements. However, the problem of closure was neither considered in detail at the design stage, nor at the stage of construction or even operation of LRWGR. There was only general understanding that the injection boreholes shall be sealed and monitoring of waste spreading shall be carried out for a certain period of time. Absence of the detailed project of LRWGR closure was one of the most significant comments from IAEA expert team. From their point of view, this will hinder the actions to ensure the long-term safety. It should be noted that the existing design documents for the sites have a section concerning the closure concept, completed in accordance with the requirements of the federal codes and standards in the field of atomic energy use NP-055-14, NP-058-14. The "Program of calculation and experimental research on justification and assessment of long-term safety of deep liquid radioactive waste disposal facility" has a section dedicated to the detailed planning of facility closure. The section envisages basic research on (1) analysis of plugging materials and structures;

(2) development and testing of technical solutions on borehole plugging; (3) development of the concept of long-term monitoring.

The results of research (both laboratory studies and calculations) will enable the selection of materials for borehole plugging, construction of structures resistant to degradation in the conditions of geological environment that is altered due to interaction with LRW.

Long-term monitoring shall be carried out in the framework of a justified system of observation wells, which shall, on one hand, minimize intrusion into the geological environment, and, on the other hand, reliably detect the possible signs of LRW components spreading. Non-destructive monitoring technologies are also planned to be used in addition to the system of wells.

Study of the possibility to introduce engineering (chemical) counter-migration barriers in addition to the natural geological barriers limiting migration at the sites of LRW disposal is also planned. Functioning of chemical counter-migration barriers is based on formation of stable substances in the conditions of an environment capable to retain radionuclides.

The need for implementation of such measures will be analyzed based on monitoring results. Radiological integrated survey of boreholes was carried out at all facilities to support the safety case for LRWGR during extended operation. The surveys allowed identifying the elements that require repair or replacement. A program for extension of LRWGR operation period beyond the designated lifetime was developed. The implementation of the program is aimed at decommissioning of failed boreholes, repair of buildings and structures, and replacement of safety-important equipment. The operation period of LRWGR has been extended up to 2023 based on the results of the program implementation. These measures can also be considered as practical priority actions aimed at closure of the facilities.

Conclusion

In conclusion, it should be noted that IAEA mission on assessment of the compliance of LRW injection practice in the Russian Federation to the IAEA safety requirements has become a unique experience for both sides in terms of review of the existing disposal facilities, which had been designed, constructed and commissioned before the introduction of the requirements [3], and, therefore, could not have complied fully with these requirements.

The recommendations and suggestions of IAEA mission have resulted in over 25 specific studies and more than five experimental research programs. The work on preparation of a series of documents on long-term safety case in accordance with the international standards is underway. Correction of the LRWGR closure concept and study of separate technologies on borehole decommissioning has started. The implemented measures on development of the LRWGR safety case, which existed before the introduction of IAEA RW-requirements, will give the chance to confirm their compliance with international safety standards.

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