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# INTERNATIONAL COOPERATION ON RADIOACTIVE WASTE DISPOSAL IN CRYSTALLINE ROCKS (CRYSTALLINE CLUB)

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*The paper presents some materials from the second meeting of the Crystalline Club (CRC/IGSC/NEA OECO). It considers construction and operational stages of the Underground Research Laboratory excavated in crystalline rocks drawing on the example of Mizunami URL (Japan). It also considers an important problem dealing with transport modeling in the fractured rock. Real data from an experiment are used to build a stochastic discrete fracture network (OFN). Migration of radionuclides is modelled both within OFN and within equivalent pore medium following OFN.*

**Key words:** *radioactive waste, crystalline rock, fracture network, modelling, underground research laboratory (URL), stages of URL life cycle, investigations in URL.*

Deep radioactive waste (RW) disposal facilities are basically designed to isolate the most hazardous radioactive waste from the biosphere using a combination of engineered and natural barriers. Crystalline rocks are considered as a geological formation suitable for such disposal. It is this formation that was chosen for deep geological repository siting in Russia. The corresponding rocks are characterized by high strength, low sensitivity to heat, low water permeability and solubility. Although fractures are quite characteristic for all types of crystalline rocks, the conductivity of such fractures may be altered through the use of engineered barriers, such as RW matrix and buffer materials with low permeability.

Many countries are considering the opportunities for siting such RW geological disposal facilities in crystalline rocks. And although quite extensive scientific, engineering and geological knowledge has been accumulated to date, there are still some areas requiring further research. In 2017, to join efforts in planning and carrying out research, as well as evaluating and interpreting relevant results Crystalline Club (CRC) was set under the auspices of the OECD's (the Organization for Economic Cooperation and Development) Nuclear Energy Agency under its Integration Group for the Safety Case (IGSC) [1].

The Crystalline Club considers relevant steps aimed at arranging the exchange of information, including the development of approaches/methods for experimental research and numerical modeling, designed to gain better understanding of crystalline rock properties supporting their use as a host formation for the disposal of high-level waste (HLW) as its main task. It is for this very purpose that the Club is now compiling a set of publications under a comprehensive report titled as the Report on the Status of R&D in CRC Countries Investigating Deep Geologic Disposal in Crystalline Rock.

Apart from the introduction and conclusion, the collection will include 5 chapters devoted to:

- International research projects investigating crystalline rocks seen as a bedrock for deep radioactive waste disposal facilities (DRWDF) siting, as well as relevant features of disposal concepts, regulatory rules and requirements, experience in research gained by various countries.

- Methods for crystalline massifs' field surveys, including relevant engineering aspects of such activities and studies supporting the excavation (for example, construction of concrete lining during the excavation of vertical shafts and horizontal galleries, characterization of the excavation damaged zone), as well as relevant experiments carried out in underground research laboratories (URL). DRWDF closure methods, such as plugging and backfilling of voids in the disposal cells are considered as well.
- Safety functions inherent to the geosphere and requirements to the properties of the crystalline bedrock ensuring its favorable interaction with the materials used to construct the engineered safety barriers. Thermal, hydrogeological, mechanical and chemical conditions favorable for the long-term preservation of the protective properties associated with the geological environment and engineered safety barriers (ESB) and especially with the bentonite buffer being considered as the main ESB component are discussed in the Report.
- Approaches and software tools applied to model ESB system and the geological environment when evaluating DRWDF safety are considered. The greatest attention was paid to the means applied to model the systems of cracks and the transfer of radionuclides in a fractured medium.
- Modeling uncertainties with fracture system being considered as their main source.

In 2018, a meeting of the Crystalline Club was held in Japan at the site of the Mitsunami Underground Research Laboratory. In addition to the issues associated with the development of the aforementioned Report, the meeting involved two thematic sessions devoted to Japanese URL excavated in granite rocks (Mitsunami), as well as the discussion of relevant issues associated with studying and modeling groundwater flows and contaminant transfer in the fractured rock mass.

## Construction arrangements and operation of Mitsunami URL

Mitsunami URL is located in the middle of the country in the vicinity of the Mitsunami city in Gifu Prefecture. This site has been already used for research by local geophysical center with 4 shallow (300 m) exploratory wells constructed. It is a general-purpose URL, i. e. no DRWDF is supposed to be built at the site. Mitsunami URL was established to address the following goals [2]:

- investigating the granite rock mass and developing a methodology enabling to test the suitability of geological disposal technologies in crystalline rock (granites);
- development of a method for assessing and demonstrating the safety of the deep disposal method based on URL investigations;
- demonstrating the adequacy of the conclusions regarding the feasibility of the RW geological disposal project to the general public.

Geoscientific studies aimed at addressing the main tasks set forth under the URL project were carried out in 3 stages, corresponding to the stages of the URL life cycle. In addition, it should be noted that an iterative approach was actually applied in the Mitsunami URL to study the geological environment. At each stage, a same sequence of actions is repeated, namely: concept — planning — research — analysis and modeling — assessment, but each time taking into account the newly gained information [2]:

Stage 1. Surface studies or pre-construction activities. At this stage, the main tasks were, firstly, to develop geological, hydrogeological, geochemical and mechanical models of the host geological environment based on the results of various studies carried out on the surface. This stage enabled to identify most informative research methods under given conditions. Secondly, to develop a detailed concept for the proposed facility, including the layout of underground structures. Thirdly, to develop a detailed plan of research to be implemented under the next stage.

Available geological data on the siting region, including previously conducted uranium deposit explorations owning to the availability of uranium oxide in local granite rocks served a basis enabling to form the initial understanding of the site's geological structure. At this stage, the following activities were carried out:

- examination of existing wells aimed at obtaining information on the geological structure of the site, evaluating mechanical properties of the rock and identifying structural disturbances;
- geophysical studies on the surface using electromagnetic and seismic-acoustic methods carried out to identify the boundaries of lithological heterogeneities and faults;
- drilling of 3 new deep (1,350 m) wells to gain more precise information on the geological structure of the rock mass and its lithological composition. Drilling was accompanied with oriented core sampling with resulting samples being subsequently subject to laboratory studies to determine mechanical, petrophysical, chemical and sorption properties of the granite;
- mechanical tests in the wells to identify stresses within the rock mass;

- tomographic cross-well surveys to identify the position and geometry of the identified heterogeneities;
- cross-hole hydraulic tests to assess the hydraulic properties of the massif and its constituent rocks.

At this stage, the foundation was laid for the system of hydrological (surface water, as well as groundwater pressure in the wells) and geochemical monitoring.

Stage 2. Stage of URL construction. At this stage, geological models developed at the previous stage were modified taking into account the data gained during excavation. At this stage, the impact of construction activities on adjacent geological formations was evaluated, as well as the effectiveness of the engineering technologies applied with an R&D program being under development.

URL shafts were constructed using blasting method: one blasting involved crushing and excavation of a rock amount corresponding to the sinking of 1.5 linear meters of a mine shaft. Walls of the mine shafts and galleries were subject to geological survey and photographing activities after each two consecutive blasts which was followed by concreting and plugging of aquifers using various materials, including bitumen.

Geological surveys involved visual detection and description of lithological heterogeneities and their boundaries, weathering zones, distribution of water-conducting fractures, faults and dikes. Rock samples were also taken for laboratory studies: chemical analysis, analysis of petrographic and mineralogical properties of the base rock and rocks filling the cracks, pore water samples for geochemical analysis. This resulted in an important outcome: the geochemical model now accounted for the distribution of waters varying in their geochemical composition by depth.

Deep bench marks were installed to monitor the stress-strain state of the rock mass, to determine stress concentration zones on the cracks in the shafts, excavations and purpose-drilled boreholes branching from shafts and galleries.

Mechanical stresses within the rock mass were estimated at different depths using hydraulic fracturing and seismoacoustic methods. These studies were carried out at a distance from research galleries to avoid the effects associated with construction activities.

Hydrogeological studies at this stage were aimed at investigating the changes in the hydraulic state of the massif resulting from relevant construction activities [3]. This was done by evaluating water inflow into mines and purpose designed wells drilled from research galleries with some hydraulic tests being performed as well.

Stage 3. Experiments conducted in the URL or the operational stage. At this stage, testing and modification of host geological formation models by applying the data from the R&Ds performed was continued. Possible impacts associated with research galleries expansion on the distribution of stresses within the rock mass were evaluated, as well as the effectiveness of engineering technologies applied at great depths.

As the result of construction activities, the following structures have emerged:

- Two 500-meter-deep vertical shafts with one of them equipped with an elevator and the other featuring a staircase;
- A 300-meter-long gallery reaching the depth of 500 m;
- Research chambers at a depth of 100 and 300 m.

Under the activities performed geodynamic, geochemical and hydraulic monitoring systems were also fitted.

Mitsunami URL construction cost amounted to 3 million $.

Operational stage involved the following studies and experiments:

- Study of technologies aimed at reducing the groundwater inflow into a gallery using cement-based sealing mixtures. Different cement mixture compositions were applied in vertical shafts at different levels and in horizontal galleries. The effect produced by the cement materials on the flow rate was evaluated.
- Tracer experiment in a gallery at a depth of 300 m using a purpose-drilled well. Its results were used to develop a model presenting a network of fractures, as well as to simulate mass transfer along it.
- Development of a technology enabling to backfill and seal (plug) the galleries being viewed as an integral part of repository closure methodology and technology. In particular, the experiment involved a study on the restoration of hydrological and geochemical conditions in granite. The studies performed were compiled into a safety case draft, as if a DRWDF was actually supposed to be built at this site and submitted for an international review [4].

## Field data on the geological environment and its application in modeling contaminant migration in fractured media

For DRWDF siting purposes, gaining knowledge on the underground fracture network assumed under the facility's scale and achieving its proper understanding is viewed as a quite important task to accomplish. Data on the fractures is generated based on observations performed in exploratory wells, excavations and tunnels. Such data is always spatially limited with a stochastic model being required to enable the interpolation of the fracture network and fracture properties. Such models developed in Japan (NUMO) and the USA (SNL) were presented at a meeting of the Crystalline Club by relevant groups of experts.

To simulate filtration and migration in a fractured medium, both groups developed a discrete fracture network (DFN) for a region covering an area of 100 × 150 × 100 m with a tunnel located in the middle. Model parameters were taken based on real data obtained in Mitsunami URL during an experiment focused on technology allowing to seal galleries [4], namely:

- based on fracture traces observed on the walls of the tunnel;
- based on fracture traces observed on the walls of a well drilled in parallel with the tunnel;
- based on pressure values determined in 6 intervals of the well depth according to packer-based measurements;
- based on the measurements enabling to evaluate water inflow into the research section of the tunnel.

For the fractures found on the walls, the following parameters were measured: position, length, drop, shear, flow rate range. 2,023 fractures were detected on the tunnel walls, water inflow was observed in 146 of them. It was assumed that fractures with no flow rate detected are either blind or insulated from the fracture network.

Approaches applied for the model development were somewhat different. American experts identified 2 sets of cracks with an observed flow rate of more or less than 1 l/min [5]. The radius of cracks was determined based on the analysis of the trace length. It was found that the best way allowing to describe the distribution of trace lengths in these sets including non-conductive cracks is a lognormal distribution. In this case, cracks with a flow rate of more than 1 l/min have an average radius of 3.9 m and a standard deviation of 2.2 m, whereas cracks with a lower flow rate have an average radius of 1.4 m and a standard deviation of 1.3 m. A correlation was assumed between the equivalent radius of the crack ($R$), its conductivity ($k$) and its aperture ($b$):

$$k = \gamma_1 \cdot R^{\omega},$$

$$b = \gamma_2 \cdot R,$$

where $\gamma_1$, $\gamma_2$ and $\omega$ are the coefficients calibrated based on the observed inflow to the tunnel. For the data obtained in the Mitsunami URL: $\gamma_1 = 1.55{\cdot}10^{-12}$, $\gamma_2 = 1.16{\cdot}10^{-5}$ and $\omega = 2.3$. Estimates of fracture permeability were confirmed based on a comparison with the results of packer tests on fractures identified in the well. High permeability values were identified in the areas with cracks being present both inside the tunnel and the well.

Discrete fracture network model includes:

- Cracks observed in the tunnel and in the well. Each of these cracks is characterized by its own particular exact location with nevertheless random properties (radius, conductivity, aperture), the distribution characteristics of which were determined based on the evaluation of the observed crack properties.
- Stochastic cracks generated on the basis of crack size, orientation, intensity and properties derived from crack analysis. Their position was assumed to be different under different realizations.

Japanese experts have identified 3 types of cracks: "continuous flow" cracks with a flow rate of more than 1 l/min, "dripping" with a flow rate of more than 0.1 l/min and "wet" with a flow rate of less than 0.1 l/min [6]. Statistical parameter characteristics were identified for each type of cracks: direction, length, permeability. A power function was used to present the length distribution:

$$f(r) = \frac{b-1}{1}\left(\frac{1}{r}\right)^{b},$$

where $r$ is the radius, $b$ is the factor chosen based on field data according to the trace lengths in the observed cracks. The number of generated cracks should correspond to the observed density. Permeability ($T$) has a common distribution for all types of cracks:

$$T = \log \text{norm}(\mu, \sigma) \cdot r^{c},$$

where $\mu$ and $\sigma$ are the lognormal distribution parameters, and c is the power-law parameter. All of them were selected in a way so that they could conform with the local hydraulic conductivity of the rock.

Location of the cracks was randomly generated, but then the cracks crossing the well and the tunnel were moved in a way ensuring their consistency with the observed ones. The permeability of cracks was recalculated so that it could correspond to relevant flow rates and hydraulic conductivity of the well.

Under the discrete fracture network (DFN), it was assumed that the water flow and contaminant migration occur only through the network of cracks with no matrix mass being involved. In addition, each crack is considered as a two-dimensional linear object having a specific shape, size, hydraulic properties (permeability and aperture).

An equivalent continuous model (ECM) can be also used for filtration and migration simulation purposes [7]. Under ECM, individual properties of cracks are converted into a property of medium's equivalent porosity. The main goal of the ECM is viewed as to reproduce the behavior, i.e. the flow and migration, of the corresponding fracture network.

Transition to ECM model was done by American and Japanese research groups based on DFN model upscaling to enable filtration and migration modelling. Comparison of migration simulations shows that, on the experimental scale, the DFN model gives better agreement with the migration tests. However, some adequate results can be obtained from the ECM model developed based on the DFN one.

## Conclusions

The information obtained at the meeting of the Crystalline Club is most directly related to the R&Ds planned to be conducted in the URL being built at the site proposed for DRWDF construction in the Nizhnekanskiy rock mass (NKM). This is due to the fact that URL NKM is also planned to be sited in crystalline rocks (Archean gneisses).

The research program involves geophysical surveys conducted from the surface. Shaft excavation operations will go in parallel with relevant geological studies and reporting activities. During the excavation, EDZs will be monitored allowing to optimize the characteristics of drilling and blasting operations. In addition, subsequent work flows and schedules will be refined taking into account the newly obtained information.

Under safety case development procedure, computational modeling of groundwater flows and radionuclide migration in the crystalline mass taking into account its fractured structure is viewed as an important element. At the meeting, presented was an approach that could be potentially adapted to simulate filtration and migration in a system of cracks associated with NKM crystalline rock mass.

To implement this approach, up-to-date information on cracks (orientation, aperture, water flow, etc.) and interconnections in the crack system is required. To obtain this information, the following studies are planned under a series of URL hydrogeological experiments being currently developed:

- hydrogeological monitoring, which will provide information on water inflows, including those associated with fractures;
- tracer studies (single well and cluster within the same or different discontinuous faults) providing information on filtration characteristics of the fractured medium, as well as allowing relevant conclusions to be drawn on the interconnectivity level of the fracture system;
- experiments involving epoxy resin injection allowing to study the characteristics of individual cracks.

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## Bibliographic description

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