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THE BUKOV URF RESEARCH, DEVELOPMENT AND DEMONSTRATION ACTIVITIES PROGRAMME 2023

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SÚRAO

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List and explanations of abbreviations

ABI	Acoustic Borehole Imaging (a method for displaying borehole walls using an acoustic probe - television)
Äspö HRL	Äspö Hard Rock Laboratory
Bukov URF	Bukov Underground Research Facility
CCBM	Compact Conical ended Borehole Monitoring (stress measurement method using cone strain gauge probes)
CCBO	Compact Conical ended Borehole Overcoring (a method for determining the stress using conical strain gauge probes and their overcoring - borehole relief method)
DFN	Discrete Fracture Network
DGR	Deep geological repository
EDZ	Excavation damaged zone
EdZ	Excavation disturbed zone
EIZ	Excavation influenced zone
ERT	Electric resistivity tomography
OBI	Optical Borehole Imaging (a method for displaying borehole walls using an optical probe - television)
R&D	Research and development
RAW	Radioactive waste
RD&D	Research, development and demonstration
REP	Research and experimental plan
SNF	Spent nuclear fuel
SÚRAO	Czech Radioactive Waste Repository Authority (WMA)
SÚRAO R&D Plan 2020	SÚRAO Technical Report No. 525/2020: the SÚRAO medium-term research and development plan for the period 2020-2030
THMC (processes/models)	Thermo-hydro-mechanical-chemical (processes/models)
TZ	Technical report

WDP	Waste disposal package

Abstrakt

Tato zpráva popisuje dokončené, probíhající a plánované aktivity v PVP Bukov. Jedná se o aktualizaci první verze dokumentu z roku 2021 (TZ SÚRAO 546/2021). Od počátku provozu PVP Bukov je experimentální plán SÚRAO naplňován realizací jednotlivých zakázek/projektů. První část dokumentu se soustředí na popis všech jednotlivých dokončených a probíhajících experimentů, s vysvětlením jejich základní vazby na program přípravy hlubinného úložiště. Druhá část zprávy popisuje stav řešení oblastí plánu výzkumných prací, které jsou již částečně v řešení (jsou naplňovány prostřednictvím probíhajících zakázek) anebo se u nich předpokládá potřeba nové zakázky (je plánován nový nebo doplňující experiment). První dvě oblasti osahují popis aktivit týkajících se charakterizace horninového masivu a migrace látek v horninovém prostředí. Nejobsáhlejší je oblast experimentů související s inženýrskými bariérami HÚ. Do této oblasti spadají aktivity, které řeší například kompatibilitu konstrukčních materiálů s materiály ukládacího systému. Nově je v dokumentu uvedeno konkrétní doporučené technické řešení in-situ experimentů s výstavbou modelů ukládacích míst. Blíže je také popsán demonstrační experiment, kterým by měl být zakončen hlavní program provozu laboratoře.

Klíčová slova

Hlubinné úložiště, HÚ, PVP Bukov, RD&D program, bentonit, horniny krystalinika, inženýrská bariéra, buffer, backfill.

Abstract

This report provides a description of the completed, ongoing and planned activities at the Bukov Underground Research Facility (URF). The document consists of an update of the first version of the document, which was compiled in 2021 (TZ SÚRAO 546/2021). Since the commencement of the operation of the Bukov URF, SÚRAO's experimental plan has been fulfilled via the completion of various contracts/projects. The first part of this document provides a description of all the Bukov-related experiments, both completed and ongoing, accompanied by an explanation of their links to the Czech deep geological repository (DGR) programme. The second part of the report describes the situation regarding the fulfilment of those areas of the research work plan that have already been partially addressed (via ongoing contracts) and for which the requirement for new contracts is assumed (new or additional experiments are planned). The first two areas include a description of the research activities related to the characterisation of the rock mass and the migration of substances within the rock environment. The most comprehensive field of experiments concerns the research of the engineered barriers of the future DGR including, for example, the compatibility of the planned structural materials with the materials to be used in the disposal system. The document also addresses a specific technical design that has been recommended for the conducting of in-situ experiments involving the construction of models of the disposal spaces. Furthermore, the document provides a detailed description of a demonstration experiment that will conclude the main experimental programme at the laboratory.

Key words

Deep geological repository, DGR, Bukov URF, RD&D programme, bentonite, crystalline rock, engineered barrier, buffer, backfill.

1 Introductory information

1.1 Deep geological repository development and preparation programme

According to the Czech Spent Nuclear Fuel and High-Level Waste Management Concept, one of the main responsibilities of the Czech Radioactive Waste Repository Authority (SÚRAO) concerns the deep geological repository (hereinafter referred to as the DGR) development and preparation programme; the DGR will serve for the disposal of all radioactive waste that cannot be disposed of in surface or near-surface repositories. The technical design of the Czech DGR was inspired by the Swedish KBS-3 concept as adapted to the requirements of the Czech environment (Hausmannová et. al 2023). The Czech DGR will be constructed in a crystalline rock body located in the Bohemian Massif.

SÚRAO is conducting the research, development and demonstration activities required in the context of the extensive DGR development programme. A description of the various activities involved is provided in the SÚRAO Medium-term Research and Development Plan for the period 2020-2030 (hereinafter referred to as the SÚRAO R&D Plan 2020; Vokál et al. 2020), which followed up on the Medium-Term Research and Development Plan for the needs of the Siting of the Deep Geological Repository in the Czech Republic 2015-2025 (Pospíšková et al. 2015), on the basis of which a wide range of research projects have been initiated and conducted to date. The SÚRAO 2020 R&D Plan takes into account the requirements of the latest update of the Spent Nuclear Fuel and High-Level Waste Management Concept in the Czech Republic as approved by Government Resolution No. 597 of 26 August 2019 and the requirements of the new Atomic Act No. 263/2016 Coll. and the various implementing regulations thereof. The plan covers primarily the period up to the selection of the final site for the DGR, i.e. approximately up to 2025 - 2030.

1.2 SÚRAO’s RD&D activities in underground facilities

The research and development activities associated with the planning and construction of deep geological repositories necessarily involves the collection of data from the rock environment and the conducting of in-situ experiments in underground research laboratories situated in similar rock environments to that anticipated for the construction of the DGR. Since the commencement of the DGR development and preparation programme in the Czech Republic in the 1990s, SÚRAO has obtained invaluable methodological experience via its participation in projects performed in foreign underground laboratories (e.g. the Grimsel Test Site, Schneeberger et al. 2019) and, more recently, research conducted in underground facilities in the Czech Republic.

The Czech DGR programme was inspired by the approaches adopted by countries with more advanced DGR development programmes and follows a proven procedure for the development of the DGR, an essential component of which comprises the implementation of a detailed RD&D programme in Czech generic underground research facilities. Although the basic approach adopted by all states with nuclear programmes involves disposal in deep geological repositories based on the multi-barrier concept, the specific technical design of each facility depends on the local conditions (natural, economic, political) and the respective radionuclide inventory. The development and testing of country-specific DGR technical designs requires research in generic underground research laboratories, which are used in the early stages of the development of deep geological disposal facilities and are often adapted from otherwise unused underground spaces, or at least make use of the existing infrastructure of underground complexes, which results in significant financial savings with concern to both their construction and operation. Generic laboratories are generally not located near to the planned site of the future DGR; moreover, their purpose differs from that of so-called site-specific (OECD-NEA 2013) laboratories for the testing of the conditions of specific rock formations considered for the construction of the DGR and the underground spaces within the DGR complex. The main objective of generic laboratories concerns the timely development and verification of the DGR technical design aimed at ensuring that the DGR construction project at the finally-selected site is feasible within the planned time horizon.

In previous years, the SÚRAO RD&D programme in the Czech Republic involved the conducting of research primarily in the Bedřichov tunnel (Hokr et al. 2018) and the Josef underground laboratory (Svoboda et al. 2016, Šťástka et al. 2020). Research was also conducted at the Melechov location; rather than an underground complex, however, the Melechov site comprises a network of deep boreholes drilled from the surface, which provide ideal conditions for the research of the properties of crystalline rocks using surface-based and borehole measurement methods (Rukavičková et al. 2006, Komulainen et al. 2019). Subsequently, aimed at best approximating the real conditions of the future Czech DGR for the conducting of in-situ experiments, it was decided to construct the Bukov Underground Research Facility at a depth of approximately 500 m below the surface. Fig. 1 shows the locations of the above-mentioned underground facilities together with recommended and backup sites for the construction of the DGR.

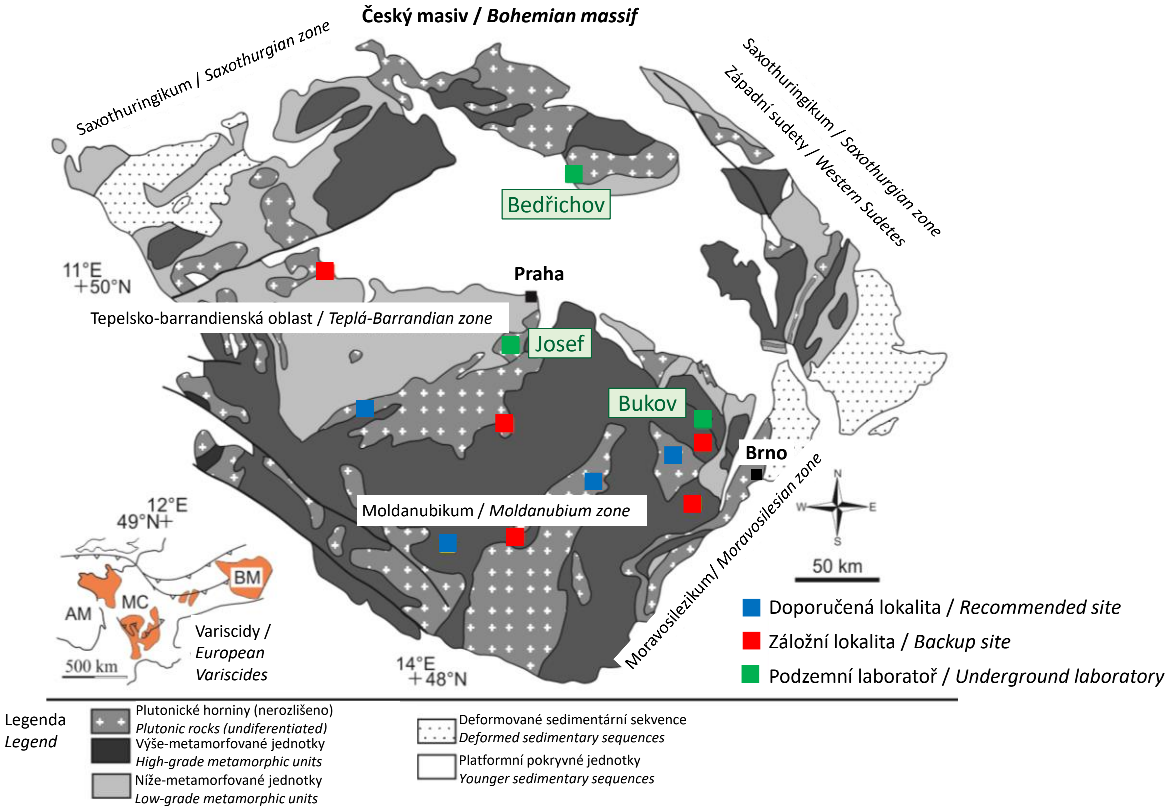

Fig. 1 – Geological map of the Bohemian Massif indicating the locations of the DGR candidate sites and underground laboratories

In order to demonstrate the usability of the final site selected for the DGR from the perspective of long-term safety, it will be necessary to construct a set of credible models for the prediction of the development of the proposed disposal system into the future (Mikláš et. al 2023). This model will be used to demonstrate that, during the anticipated development of the DGR over the long term, the exposure of a representative person (all exposure pathways) will not exceed 0.25 mSv/year (according to Act 378/2016 Coll. section 18 (1) and Act 263/2016 Coll. section 82 (1)). The set of models will include geological, tectonic, hydrogeological, geomechanical, geochemical and THMC models. In order to develop the required modelling tools and to verify their functionality, it will be necessary to obtain the most relevant data available, preferably from in-situ measurements. SÚRAO's own comprehensive system of modelling tools, which are currently in the development phase, must be available during the period in which work is conducted at the final site for the DGR. The accuracy and reliability of these tools in terms of the long-term prediction of the development of the DGR will have to be verified in advance, concerning which the use of generic laboratories is only way in which to obtain the relevant data for these models in the time available.

As part of a series of studies conducted in 2020, an evaluation was made of the data required, the potential for obtaining the data from various underground facilities and the degree of the relevance of the data for the Czech DGR development programme (Pospíšková et al. 2020a). The foreign underground laboratories Äspö HRL, Mizunami, Onkalo and the Grimsel Test Site, as well as the Czech underground laboratories Josef and Bedřichov, including the Melechov test site, were subjected to analysis and compared with the Bukov URF. The facilities were compared in terms of the potential for obtaining the data required to construct credible models and to prove the technical feasibility of the DGR. The analysis revealed that it would be possible to obtain the comprehensive set of data required to construct and verify models for the demonstration of long-term safety and the feasibility of the technical concept of the DGR from the Bukov URF.

1.3 Structure of the report

This report is divided into chapters as follows:

- Chapter 2: Bukov URF – descriptions of the laboratory and the Rožná I mine and an overview of previous experimental plans for the Bukov URF and other relevant studies.
- Chapter 3: Description of the objectives of the Bukov URF.
- Chapter 4: Overview of completed projects – basic descriptions of the connections of the projects to the DGR, their objectives and results.
- Chapter 5: Overview of ongoing projects – basic descriptions of the connections of the projects to the DGR, their objectives and interim results.
- Chapter 6: The various areas of the R&D plan and their completion status.

2 Bukov URF

The underground laboratory is located on level 12 of the former Rožná I uranium mine complex (Fig. 2). The system of underground passages was excavated from the 1950s onwards following the commencement of uranium ore mining at the site. Mining activities were terminated in 2017. The first section of the underground laboratory (Bukov URF I), which was commissioned in 2017, is located close to the B-1 shaft directly beneath the village of Bukov. In addition to the first operational part of the laboratory, a new system of laboratory corridors (Bukov URF II) is currently being excavated in the vicinity of the B-2 shaft, the position of which was determined on the basis of the availability of suitable geological conditions as indicated by drilling exploration work, and suitable technological conditions for the conducting of experiments in the future. The state-owned company DIAMO s.p. (GEAM division) is responsible for the construction of the laboratory and its subsequent operation, as well as the maintenance of the mine infrastructure.

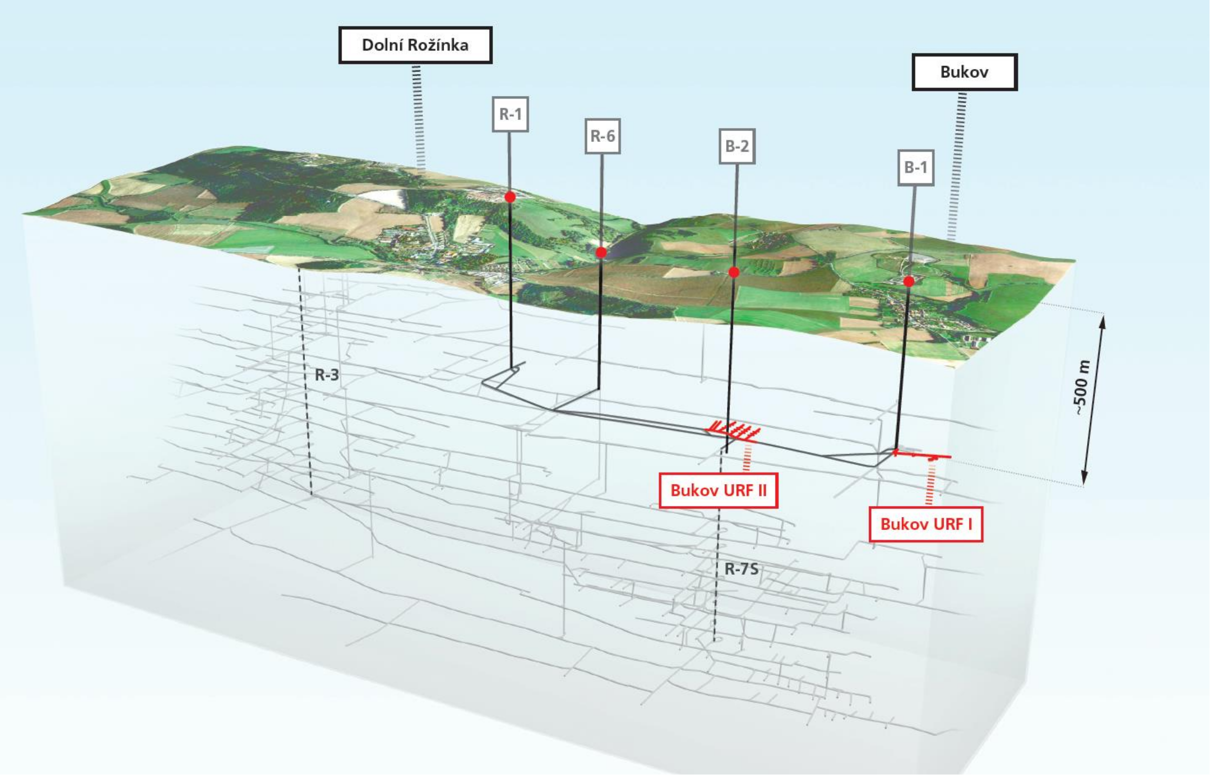

Fig. 2 – Scheme of the mine complex showing the location of Bukov URF I and Bukov URF II

2.1 Bukov URF I

The underground spaces excavated as part of the first stage of the construction of the laboratory (Bukov URF I) are located on level 12 of the mine at a depth of approx. 525 m below the surface (Fig. 2). The excavation of Bukov URF I commenced in 2013 and was completed in 2017, in which year the facility was commissioned and the experimental phase commenced. Bukov URF I comprises a total of 470 m of corridors (Fig. 3) for the conducting of experiments. The position of the laboratory within the Rožná I mine is shown in Fig. 2.

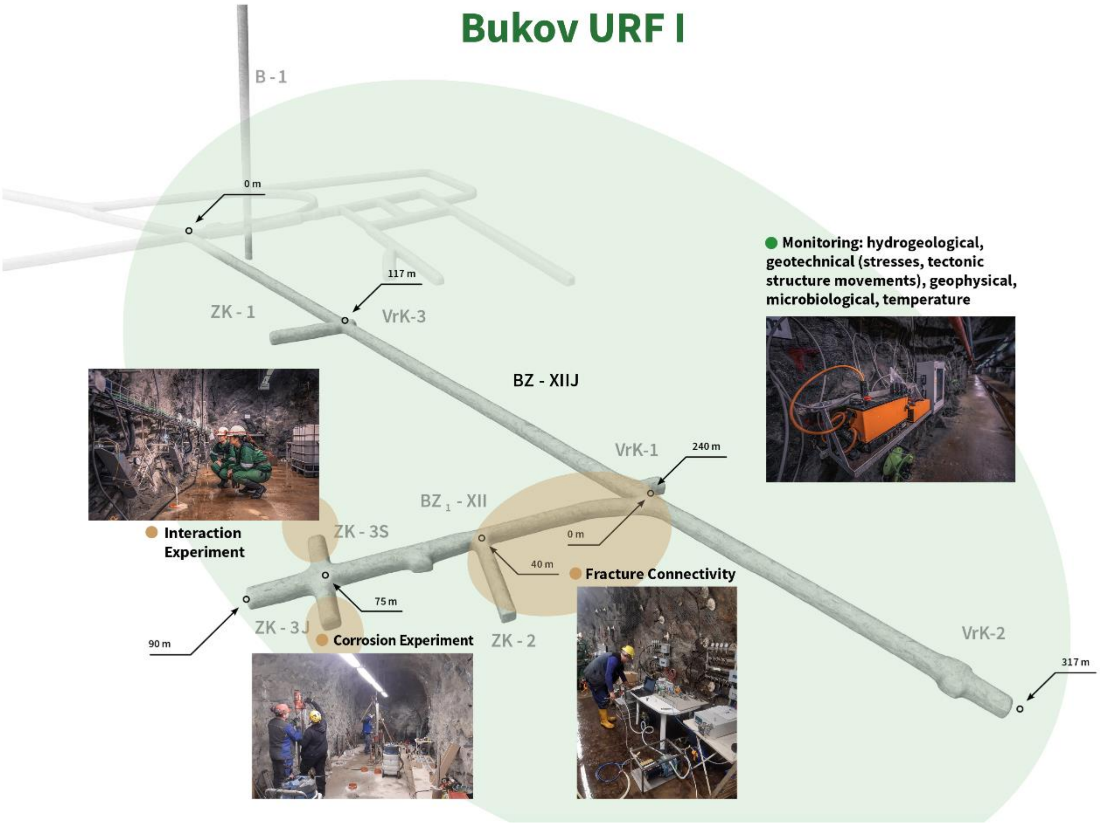

Fig. 3 – Scheme of the Bukov URF I laboratory corridors showing the locations of the key experiments

From the point of view of geology, the laboratory is located in highly metamorphosed rocks of a volcano-sedimentary complex consisting mainly of migmatite, amphibolite and paragneiss. The lithological types were determined via a petrographic analysis that formed part of the Characterisation I project (Bukovská et al. 2017). The study of samples extracted from core boreholes proved the majority presence of biotitic, amphibole-biotitic and amphibolic migmatites accompanied by occasional veins of pegmatites and granites. Hydrothermal veins containing mainly calcite, quartz and quartz-albite-adular minerals feature in the faults and fractures created as a result of tectonic disturbances throughout the whole of the metamorphic complex. Manifestations of the hydrothermal alteration of the rock, mainly the sericitisation and kaolinisation of feldspars, were also confirmed. The geochemical characterisation of the rock environment was conducted following the determination of the petrographic typology. The main components in the rock complex comprise SiO_2, stable Al_2O_3 and K_2O; MgO, CaO, TiO_2 and iron oxides are also present. The trace elements observed include Ta, Th, Nb, P, Ti and Sr. The main elements in the carbonate veins consist of Ca, Mg, Fe and Mn. The position of the laboratory was selected so that the corridors are not traversed by structures containing uranium minerals.

A network of hydrogeological monitoring stations was installed for the purpose of obtaining information on the type, chemical composition and flow of the groundwater. The excavation of Bukov URF I resulted in fluctuations in water inflows and decreases in their yield. $Ca\text{-}HCO_3$ type water predominates in the shallower parts of the Rožná I mine complex (upper levels), whereas $Na\text{-}HCO_3$ water prevails in the deeper crystalline parts. Moreover, the occurrence of $Ca\text{-}SO_4$ type water has also been confirmed. From the point of view of ductile tectonics, the overturning of two regional metamorphic foliations can be observed in the Bukov URF I rock environment and, concerning brittle tectonics, two dominant groups of brittle structures with movement indicators have been identified.

The laboratory consists of a 300 m long access corridor, which was constructed using the conventional excavation method, and a number of shorter galleries that were excavated using the smooth blasting method (Augusta et al. 2018). Most of the access corridor has been fitted with TH arch reinforcement with the bracing of the ceiling and sides. Where necessary, bolted reinforcement was installed to stabilise the walls in combination with expanded metal or mesh and, in some places, at the intersections of the corridors, with shotcrete. The laboratory galleries have not been fitted with arch reinforcement; however, fiberglass rock bolts have been installed in places with unfavourable fracture system directions.

2.2 Reconfiguration of the Rožná I mine infrastructure

Following the conclusion of mining activities in 2017, the operation of the underground workings continued as before with the continuation of access to the mine levels below the level of the laboratory, i.e. down to level 24 at depth of 1200 m, from where the continuous pumping of mine water was maintained. Access to these floors was necessary for a number of projects (Bukovská et al. 2020, Stemberk et al. 2022) that obtained unique data on changes in the properties of the rock mass with increasing depth below the surface.

SÚRAO commissioned a number of external comparative studies in 2019 - 2020 aimed at determining whether it was necessary to continue investing in the operation of the Bukov URF in order to fulfil the research and experimental plan, or whether it would be more effective to obtain the necessary data in other ways, e.g. from experiments conducted at foreign underground facilities. The technical and economic studies focused on comparing various mine operation options and addressing the question of whether to continue the costly operation of the whole of the mine or to invest in the modification of the infrastructure of a limited area, accompanied by a comparison of the economic aspects of the various options. The result was a recommendation to continue the operation of the Bukov URF under optimised conditions. Moreover, the various studies concluded that it was necessary to continue conducting experiments at the Bukov URF and to invest in changes in the operational configuration of the mine. The most economically advantageous and technically feasible solution involved flooding the lower floors of the mine up to level 13, while maintaining the operation of four shafts (R-1, R-6, B-2 and B-1). The most significant investment according to this solution concerned adapting the existing cascading system for the pumping of mine water to the surface.

Following the evaluation of the above-mentioned studies, a new contract on cooperation concerning the operation of the Bukov URF was concluded on 1 July 2020. The contract covers operation until 2030 with an option to extend the agreement up to 2035. Work was carried out in 2020 – 2022 aimed at reducing the number of operated shafts from 6 to 4. In March 2021, the pumping of water from level 24 was terminated and the increase in the water level is currently being monitored in shafts R-7S and R-3. A new pumping station has been installed in the proximity of shaft R-7S at a depth of approx. 60 m below level 12 from where the water will be pumped out via the R-1 and B-1 shafts once the water level has risen to this level. The reconfiguration work, which was completed at the end of 2022, included, for example, the replacement of selected discharge lines, the reconstruction of the transformer station near shaft B-1, the partial reconstruction of the R-1 surface pumping station, the installation of a system for the heating of inflowing air and the modification of the B-1 shaft building. Access to the mine complex is now provided only to the area between shafts R-1 and B-1 on level 12 (Fig. 4).

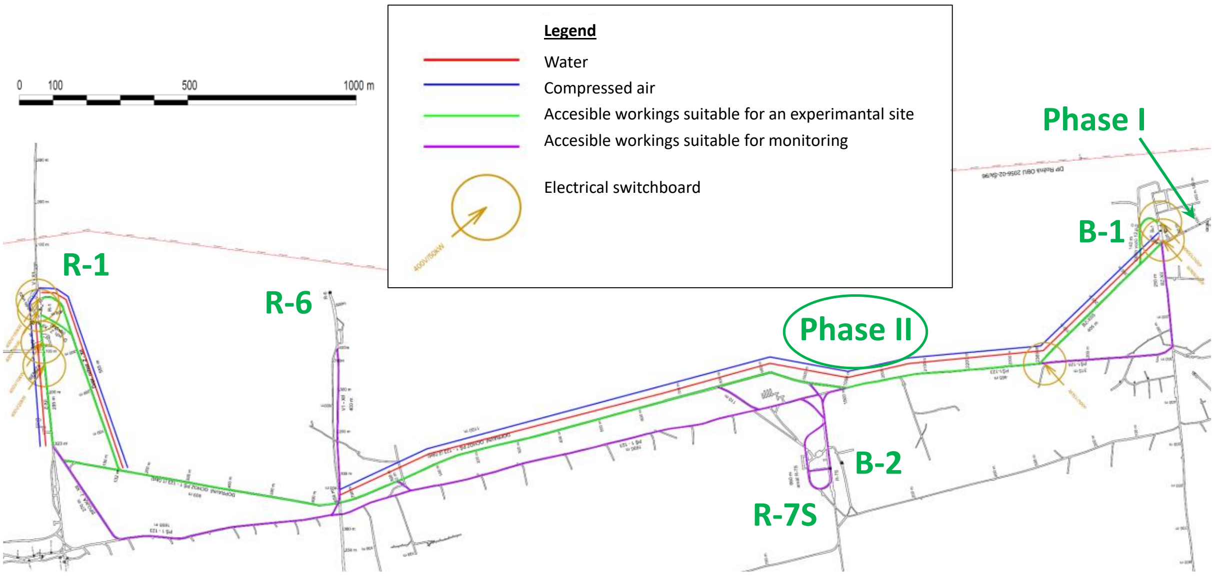

Fig. 4 – Map of the operational section of level 12 of the mine

2.3 Bukov URF II

Since Bukov URF I was deemed insufficient to fulfil SÚRAO's extensive research programme, it was decided to excavate a new complex of laboratory corridors (Bukov URF II) east of shaft B-2 (R7-S) (Fig. 2, Fig. 4). The exact location was determined on the basis of borehole exploration work.

The existence of suitable geological conditions was first confirmed at the planned location of Bukov URF II; moreover, the proximity of shaft B-2, which, due to its wide profile, can be used for the transport of oversized loads, is a further advantage of the location, particularly in connection with the planned conducting of demonstration experiments in the advanced phase of the operation of the laboratory. The affected area is shown in Fig. 4, which provides a map of the section of level 12 between shafts R-1 and B-1 highlighting the corridors that will remain accessible in the future and which can be used for research activities (for example, the installation of monitoring stations). The map in Fig. 5 shows the area of level 12 between shafts B-1 and B-2 (marked Bukov URF I and Bukov URF II).

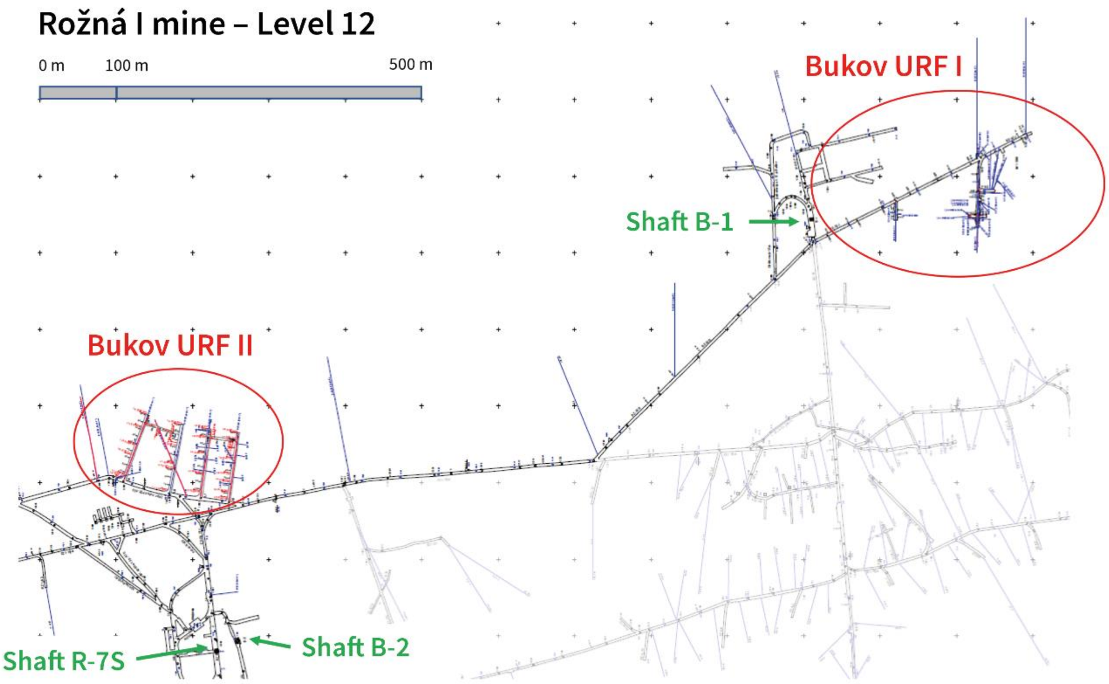

Fig. 5 – Map of the section of level 12 of the Rožná I mine between Bukov URF I and Bukov URF II

The plan for the new complex includes the excavation of six laboratory corridors (each with a length of up to 90 m), from which ten-metre long test chambers will be subsequently excavated. The lengths of the test chambers are based on the lengths of the mine corridors that can be ventilated via the natural flow of air without the need to install separate ventilation systems. Previous experience indicates that such chambers are sufficiently dimensioned in terms of installing the technological equipment required by the respective experiments and the conducting of core drilling work. The planned complex also includes ventilation corridors that that connect pairs of laboratory corridors and allow for the flow of air. The specific locations of the test chambers are being determined concurrently with the excavation process and depend on the geological structures of the laboratory corridors. A maximum number of 24 test chambers is currently considered in the excavation plan.

Pilot exploratory boreholes were drilled along the axes of the planned laboratory corridors in the second half of 2020, and in January 2021, the excavation commenced of the first two laboratory corridors. The final planned layout of the Bukov URF II corridor system is shown in Fig. 6. The map shows the state of excavation as of 1 January 2024 including the yet to be excavated workings. The excavation work, which is expected to be completed after the first quarter of 2024, will be followed by the equipping of the laboratory corridors, which should be completed during the fourth quarter of 2024.

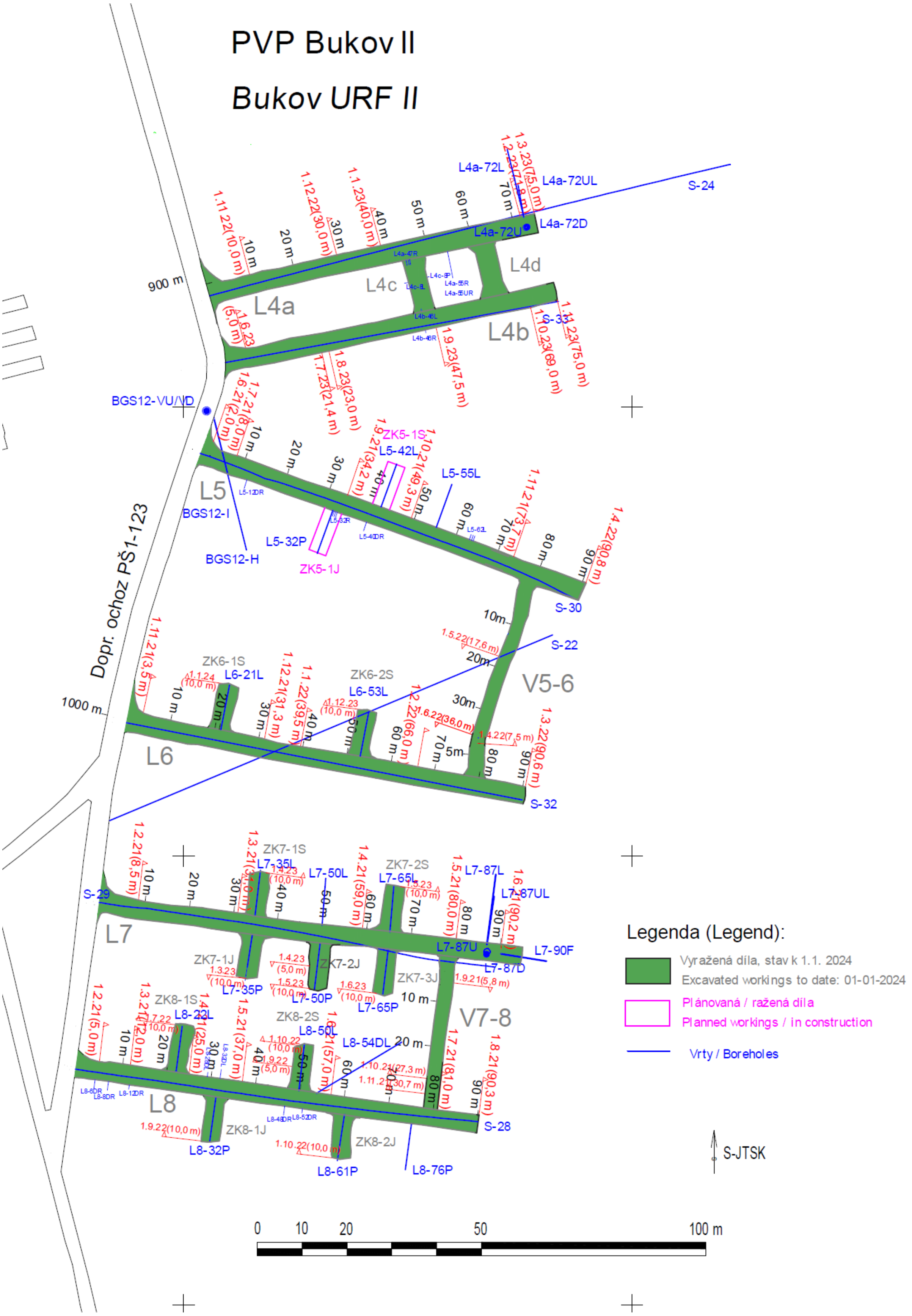

Fig. 6 – Bukov URF II

2.4 Previous studies and experimental plans at the Bukov URF

The first study concerning the implementation of the plan of experiments at the Bukov URF was drawn up in 2015 during the excavation of Bukov URF I (Havlová et al. 2015). The study included a proposal for monitoring, research and experimental work in five basic research areas, which provided the basis for the subsequent detailed breakdown of the SÚRAO research and experimental plan (see REP1 to REP5, Table 1). This programme was expanded in 2016 via the addition of a further 2 research topics following the processing of technical-economic studies, i.e. REP6 and REP7 (Vondrovic et al. 2016; ČVUT-SATRA-Mott MacDonald CZ consortium, 2016). The first update of the 2015 experimental plan was conducted in 2017 so as to include the use of the Bukov URF to provide support for the safety analysis of the nearby Kraví Hora DGR candidate site (Havlová et al. 2017).

Table 1 – Research areas and the SÚRAO experimental plan at the Bukov URF

SÚRAO programme area	**Abbreviated name**	**Objectives**
REP1	Characterisation	Development of rock environment description methodologies. Collection of descriptive geological data, its database storage and interpretation in the form of 3D models.
REP2	Monitoring	Testing and development of methods for the long-term monitoring of processes that occur in the rock mass (hydrogeology, tectonics, microbiology, seismicity, etc.). Development of non-destructive geophysical methods.
REP3	Transport	Research of groundwater flow and the transport of radionuclides in the rock environment. In-situ tests in boreholes. Development and testing of modelling tools.
REP4	Engineered barriers THMC processes	Research and development of engineered barrier materials. Research of the corrosion properties of materials intended for the WDP. Research of interactions between the engineered barrier materials (bentonite, concrete) and the rock mass. Verification and validation of THMC models.
REP5	EDZ	Development and testing of methods for the characterisation of damaged (EDZ) and disturbed/influenced (EdZ, EIZ) zones of rock in the vicinity of the underground spaces.
REP6	Technological procedures	Development of new procedures for the construction of underground workings (drilling and excavation work, grouting, excavation in fault zones).
REP7	Demonstration experiments	Complex experiments for the testing of the behaviour of the various components of the disposal system at the real

		scale and under DGR conditions. The testing of handling technologies, the construction of experimental models and the monitoring of processes.

In order to avoid the unnecessary repetition of research previously conducted at other underground laboratories with respect to the planning of experiments, a search was performed in 2018 of experiments conducted in other underground laboratories located in crystalline rocks (Butovič et al. 2018). The aim of the research was to compile a comprehensive list of the most important experiments carried out in the Äspö HRL, Whiteshell, Grimsel Test Site and Onkalo underground laboratories. The descriptions of each experiment were accompanied by an assessment of whether the results were relevant to the needs of the Czech DGR programme and whether it would be appropriate to repeat the experiment under Czech conditions (at the Bukov URF) and specifically within the next 10 years. The subsequent second update of the experimental plan reflected the information provided by the research (Svoboda et al. 2019).

In 2020, external studies were conducted by AFRY Ltd. (Pospíšková et al. 2020e), the aims of which were to:

- assess the usability of data obtained via the Bukov URF RD&D programme (Pospíšková et al. 2020a),
- assess the Bukov URF experimental plan and make cost estimates concerning its implementation (Pospíšková et al. 2020b),
- assess the technical and economic potential of the laboratory (2020c),
- perform SWOT and cost benefit analyses (Pospíšková et al. 2020d).

SÚRAO has taken into account the recommendations set out in the above studies and continues to work with the information provided.

The basis for the proposal of research in the REP4 area, which includes engineered barriers made of bentonite, comprised the Summary of the Research of Czech Bentonite for DGR use – up to 2018 (Hausmannová et al. 2018) report and a document that sets out recommendations for the research plan and developments in this field prepared by experts from the AINS GROUP and Posiva Solutions (Kumpulainen et al. 2018). The approaches to the various experiments were subsequently outlined in a technical report compiled in 2023 (Svoboda et al. 2023).

In 2020, a study containing recommendations for a monitoring and research programme that would accompany the construction of Bukov URF II was prepared under the leadership of Posiva Solutions. The first outputs of the study comprised a report that summarised the experiences of the Äspö HRL, Onkalo and other laboratories, an assessment of the research conducted during the construction of Bukov URF I and recommendations for Bukov URF II (Aaltonen et al. 2020). The second set of outputs included an evaluation of the excavation technology used in the construction of Bukov URF I and proposals for its optimisation based on experience of the excavation of underground passages at the Onkalo site (Lehtola and Aaltonen 2020).

In 2021, SÚRAO specialists prepared technical report No. 546/2021 (Smutek et al. 2021) with a detailed description of the plan of experiments, including explanations of the links to the DGR development programme.

3 Objectives of the Bukov URF research programme

The basic objectives of the Bukov URF research programme are based on the requirements defined in SÚRAO research and development plans (Pospíšková et al. 2015; Vokál et al. 2020). One of the most important objectives is to gain enough experience and data to be able to demonstrate the safety and feasibility of the Czech DGR at the finally selected site. It is planned that the Bukov URF will be operated until approx. 2035, at which time research activities will be transferred to the underground complex of the DGR at the final site.

The general objectives of the Bukov URF according to previous R&D plans (Pospíšková et al. 2015, Vokál et al. 2020) can be summarised as follows:

a) Acquisition of data for the calibration and validation of models and the verification of software tools

One of the priorities of the current stage of the DGR site selection process is to obtain the data that will allow for the demonstration of the stability and safety of the planned repository at the proposed depth below the surface. In this respect, the Bukov URF is used for obtaining the data from in-situ experiments required to develop the respective modelling tools and to verify their functionality so that a complex set of geological, tectonic, hydrogeological, geomechanical, geochemical and THMC models can subsequently be constructed to prove the long-term and operational safety of the DGR at the final site and demonstrate the technical feasibility of the project.

According to SÚJB Safety Guide BN-JB-2.4 (SÚJB, 2021), it is recommended that mathematical models be validated using experimental data. The list below provides details of the experiments at the Bukov URF that relate (or will relate) to the calibration and/or validation of mathematical models, as broken down into various experimental areas (Mikláš 2023):

- Lifespan of the WDP
    - Pilot corrosion experiment (chapter 5.4)
    - A follow-up experiment focusing on stainless steel as the material for the inner casing of the WDP (if considered necessary)
- Evolution of the bentonite barrier
    - Interaction experiment (chapter 5.1)
    - Long-term laboratory (chapter 6.4.2)
    - HEAT (chapter 6.4.3), EXP (chapter 6.4.4) and DEMO (chapter 6.4.6) experiments
- Transport through the host rock
    - Research on flow in EDZ and EIZ (chapter 6.2.5)
    - Erosion of bentonite and the transport of colloids (chapter 6.4.4)
    - Development of modelling concepts in the field of groundwater flow (chapter 6.2.3)
    - Verification of approaches to the evaluation of the propagation of the uncertainties of in-situ transport parameters (chapter 6.2.4)
- Heat transfer
    - Temperature monitoring (chapter 5.5)
    - The HEAT (chapter 6.4.3) and DEMO (chapter 6.4.6) experiments
- Geomechanics

  - Research of stress measurements at the Bukov URF II (chapter 5.7)

b) Testing and demonstration of proposed technical design solutions

The second objective is to test currently proposed technical design solutions for the DGR at an appropriate depth below the surface in a precisely described geological environment. This concerns, for example, the long-term monitoring of the corrosion of the WDP candidate materials (chapter. 5.4) and the testing of the migration properties of the rock mass and the stability of the sealing barriers.

c) Development and verification of methodologies for the study of the rock environment

The third objective involves the preparation and testing of methodologies for the study and description of the rock in a specific underground environment, which can then be applied for the description and characterisation of the DGR candidate sites and during the construction of the DGR at the finally selected site. One of the most important factors in this respect concerns the development and testing of SÚRAO's own classification system for use in the DGR project with concern, for example, to the evaluation of the suitability of the underground spaces used for the drilling of the disposal wells and the description of the isolation section of the DGR and the critical rock interfaces.

d) Acquisition of know-how of the construction and characterisation of underground workings

The final objective concerns obtaining experience and know-how from the construction of underground workings and the commissioning thereof. The use of the Bukov URF provides a unique opportunity to excavate new underground workings and allows SÚRAO experts to gain valuable experience of working in underground spaces and to obtain feedback from solving complicated technical tasks in the early phase of the DGR development programme.

The various objectives of the Bukov research programme were further broken down in the SÚRAO R&D Plan 2020 (Vokál et al. 2020) into the following priority research areas:

1) **Determination of the transferability of the knowledge obtained from the surface parts of the Bukov URF rock environment to the deeper parts of the rock mass in order to predict the properties of the DGR candidate sites at the planned depth of the repository**
   This research area refers to obtaining information on the local properties of the rock mass from the surface to the depth at which the DGR will be constructed (possibly deeper) for the prediction of the properties of the DGR candidate sites and the classification of the rock mass itself. The research involves the study of archive documentation from the period of operation of the Rožná I mine and the conducting of projects that provide information on the geological, hydrogeological, geomechanical and other properties of the rock mass, which, together, provide a comprehensive picture that is expanded and refined on a continuous basis. To date, the most relevant data in this respect has been obtained from the Characterisation I (chapter 4.1) and Deep Horizons projects (chapter 4.4). Furthermore, research is underway aimed at obtaining data for the development and refinement of transport models of the rock environment. In addition to hydraulic testing and monitoring, which is essential for the creation and calibration of hydraulic models, data is being obtained for the development of a fracture network modelling methodology and the incorporation of migration

parameters into transport models (chapter 5.2). Both laboratory and in-situ tests and monitoring (in-situ migration experiments, the monitoring of stress in the rock mass, etc.) are underway.

2) **Evaluation of the development of microbial activity (original and introduced) based on monitoring**
   Initial information on this research area was provided by the Microbiology I project (chapter 4.3). Microbial activity is also being monitored in the Interaction Experiment (chapter 5.1). The Microbiology II project (chapter 4.8) focused on the evaluation of the composition of the microbial settlement of water under anaerobic conditions and the interpretation thereof in terms of its composition and the hydrochemical conditions in flooded monitoring boreholes. Microbial activity is also considered in other experiments underway at the Bukov URF, e.g. the ongoing Corrosion Experiment (chapter 5.4).

3) **Verification of heat transfer in the DGR using sources that simulate SNF**
   The verification of the heat transfer in the DGR using sources that simulate the residual heat generated by SNF. This factor is of key importance in the DGR project in terms of its exerting an impact on the layout and dimensions of the underground corridors and disposal wells. The in-situ experiments described in chapter 6.4.3 will aim to address this issue.

4) **Verification of the prediction of the transport of mobile radionuclides in the isolation part of the DGR**
   A series of experiments that focus on the study of the advective and diffusive transport of substances will be conducted in order to verify the prediction of the transport of mobile radionuclides in the isolation part of the DGR. The experimental programme will include the performance of tracer tests using both inactive and active substances (chapter 6.2).

5) **Verification of the properties of the WDP materials under real rock environment conditions**
   The experimental programme for the verification of the properties of the materials used in the production of the WDP under real rock environment conditions is underway and forms the subject of the Corrosion Experiment (chapter 5.4).

6) **Verification of the prediction of THMC processes under real DGR conditions**
   Special in-situ experiments will be designed in connection with the verification of the prediction of THMC processes under real DGR conditions; the experiments will be planned based on the requirements for obtaining specific data for mathematical modelling purposes as defined in the respective chapter of the SÚRAO R&D Plan 2020 in the section that describes research support for the safety assessment of the DGR.

7) **Verification of the impact of mining work on the extent of damage to the rock mass (EDZ) and the insulation ability of the rock**
   The final objective concerns the verification of the influence of the excavation of underground spaces on the extent of the damaged zones of the rocks in the vicinity of the underground corridors. This topic is being addressed on a continuous basis; the most relevant information has been provided to date by the characterisation work and

research that is accompanying the construction of the new laboratory corridors of the Bukov URF II. This topic is also being addressed in the Characterisation II project (chapter 5.3) and it is planned that additional experiments will be conducted as required (chapter 6.1.2).

4 Completed projects

This chapter provides an overview of the projects that have already been completed at the Bukov URF. An explanation is provided for each project concerning its links to the DGR programme and its objectives, the research approach and selected results. An overview of the projects completed to date and financed by SÚRAO is provided in Tab. 2. An overview of external projects completed to date at the Bukov URF financed by other programmes is provided in Tab. 3.

Table 2 – Overview of completed SÚRAO projects at the Bukov URF

Name of SÚRAO project/contract	**Working name of the project**	**Duration**	**Main area of the SÚRAO research programme**	**SÚRAO technical report (TZ)**
Comprehensive geological characterisation of the Bukov URF	Characterisation I	2013 - 2017	REP1	191/2017 (Bukovská et al. 2017), 221/2018 (Souček et al. 2018)
Creation and monitoring of EDZ during the construction of the Bukov URF	EDZ I	2015 - 2018	REP5	351/2019 (Staš et al. 2019)
Microbial screening of the Bukov URF and Rožná mine	Microbiology I	2017 - 2019	REP2	382/2019 (Steinová et al. 2019)
Acquisition of data from the deep horizons of the Rožná mine	Deep horizons	2017 - 2020	REP1	464/2020 (Bukovská et al. 2020)
Hydrogeological and hydrochemical monitoring of groundwater and mine water in the Bukov URF	Hydromonitoring I	2018 - 2023	REP2	679/2023 (Vylamová et al. 2023)
Long-term monitoring of the rock mass in the Bukov URF using non-destructive geophysical methods	Non-destructive geophysics	2018 - 2022	REP2	636/2022 (Bárta et al. 2022)
Monitoring of the activity of brittle structures in the Bukov URF and the Rožná mine	Brittle structures	2018 - 2022	REP2	640/2022 (Stemberk et al. 2022)
Monitoring of anaerobic microbial settlement in the Bukov URF and research into the links between the rock environment and microbes	Microbiology II	2020 - 2021	REP2	547/2021 (Steinová et al. 2021), 552/2021 (Černá et al. 2021)

Determination of the spatial homogeneity of the environment before carrying out blasting work using seismic tomography	Seismic URF II	2020 – 2021	REP1	548/2021 (Chabr et al. 2021)
Posiva Flow Log measurements in four boreholes at the Bukov underground research facility in the Czech Republic	POSIVA FLOW LOG	2022	REP3	646/2022 (Komulainen et al. 2023)

Table 3 – Overview of external projects conducted at the Bukov URF

Name of project/contract	Working name of the project	Duration	Main area of the SÚRAO research programme	Reference
Development of geotechnical and geophysical methods for obtaining 2D and 3D images of geological structures	GEOSTAB	2017 - 2021	REP2	https://starfos.tacr.cz/cs/projekty/FV20294
Long-term research of geochemical barriers for nuclear waste disposal	GEOBARR	2018 - 2022	REP1	ÚGV MUNI, 2023

4.1 Characterisation I (2013–2017)

Project name: Comprehensive geological characterisation of the Bukov URF

Participants: Czech Geological Survey; Institute of Geonics, Academy of Sciences of the Czech Republic; ÚJV Řež, a.s.; SG Geotechnika, a.s.

Links to the DGR programme

When excavating the underground spaces of the DGR, it will be necessary to apply methods that have been proven in practice to characterise the rock mass. Due to the specific character of underground complexes such as the DGR, it will be necessary to adapt currently commonly-employed characterisation methods. The ongoing excavation of the underground spaces of the Bukov URF provides ideal realistic conditions for the testing of such methods.

Objectives

- The conducting of a multidisciplinary evaluation of the properties of the rock environment of the Bukov URF and other parts of the Rožná I mine.
- The acquisition of data and information that is detectable only during excavation or shortly after the creation of new underground passages, for example concerning the redistribution of in-situ stress.
- The description of changes in the properties of the rock mass with depth below the surface (for example, the chemistry and age of the groundwater).
- The creation of a network of points for the long-term monitoring of selected rock parameters (for example, geostatic stress and hydrogeological parameters).

- The creation of 3D models of the environment (geological, structural-geological and geomechanical).

Research approach

- The application of geological (Bukovská et al. 2017) and geotechnical methods (Souček et al. 2018).
- The analysis of the petrological and mineralogical composition of the rocks, including the characteristics of the mineral fillings of tectonic zones and the estimation of the temperature-pressure conditions of the metamorphic development, the evaluation of the petrophysical properties of the rocks, the spectral analysis of drill cores and the radiometric dating of the main geological processes. The comprehensive structural analysis of elements of ductile and brittle tectonics, including the application of the magnetic susceptibility anisotropy method. Hydrogeological mapping and the determination of the transport characteristics of the rocks. The creation of a structural-geological and geomechanical model.
- Geotechnical laboratory and field work aimed at determining and evaluating the physical-mechanical properties of rock samples taken from the walls of mine corridors, boreholes and surface locations. The determination of the stress state and deformation behaviour of the rock mass applying the hydraulic fracturing of borehole walls (hydrofracturing), Goodman Jack and CCBO (CCBM) methods. The taking of long-term periodic tensometric and convergence measurements. The determination of the quality of the rock mass according to the RQD, RMR and Q index geomechanical classifications. The assessment of the influence of technical and mine-induced seismicity on the rock mass.

Results

- The environment displays a high degree of variability in terms of the geological properties that enable the conducting of experiments. The Bukov area contains migmatitised biotite-amphibole paragneisses with occurrences of amphibolites, amphibole and biotite migmatites with variable intensities of migmatisation. Veins are often present in migmatites, and the rocks around faults show signs of secondary mineralisation. In terms of the geochemical and mineralogical composition, the rocks have been interpreted as making up the original part of a volcanic-sedimentary complex with alternating positions of basic to intermediate rocks. The analysis of the chemical composition of the secondary mineralisation and fillings of the tectonic zones revealed that they comprise products of alteration processes.
- The measurement of the magnetic susceptibility of the samples proved the assumed anisotropy with respect to the foliation directions of the rock. From the point of view of ductile tectonics, the refolding of two original regional metamorphic foliations was observed. Concerning brittle tectonics, two dominant groups of brittle structures with movement indicators (faults and shear fractures, Fig. 7) were identified.
- The research of the groundwater types in the vertical profile of the site (from the surface to a depth of beyond 1200 m) demonstrated changes in the chemistry with depth, with a transition from $Ca\text{-}SO_4$ type water, through $Ca\text{-}HCO_3$ and $Na\text{-}HCO_3$ to $Na\text{-}Cl$ (Fig. 8). The repeated sampling of water from inflows to the Bukov URF corridors over a period of 2.5 years revealed a shift in the water composition from $Na\text{-}HCO_3$ type to water with an enhanced sulphate content.

- The laboratory analysis of the rock transport parameters yielded results in relation to both diffusion and sorption processes. The results did not reveal the significant influence of differing lithologies or the variable internal structure of the rocks on the effective diffusion coefficient values. These parameters are more dependent on the mineralogical composition and the degree of transformation than on the internal anisotropy.
- The in-situ stress ranges were determined (max. horizontal stress 16.5 – 31 MPa, min. horizontal stress 10 – 17 MPa) by applying various stress determination methods (hydraulic fracturing, measurements in boreholes using cone strain gauge probes during the overcoring of boreholes, the analysis of convergence measurements).

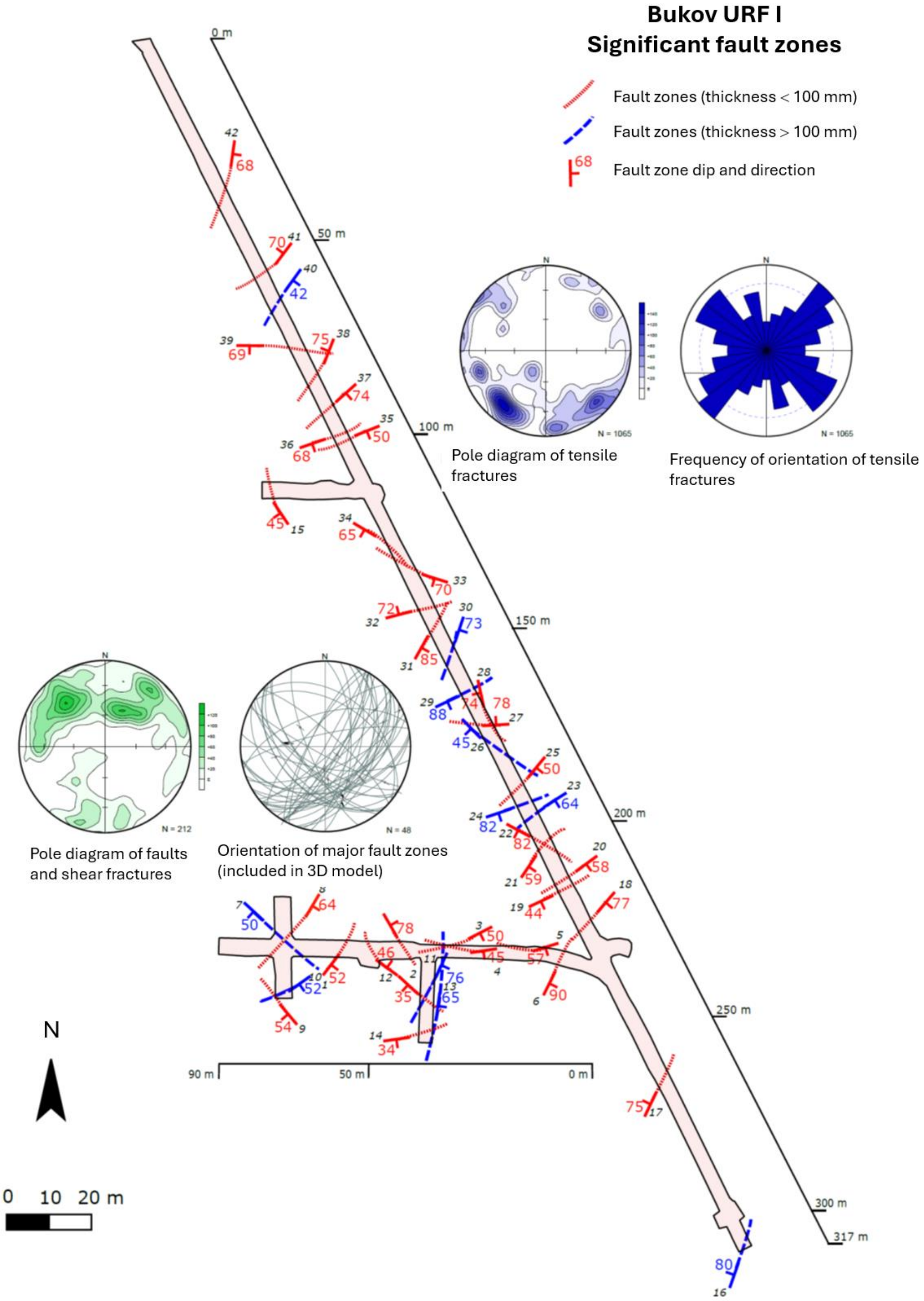

Fig. 7 – Significant fault zones and fractures in Bukov URF I (Bukovská et al. 2017)

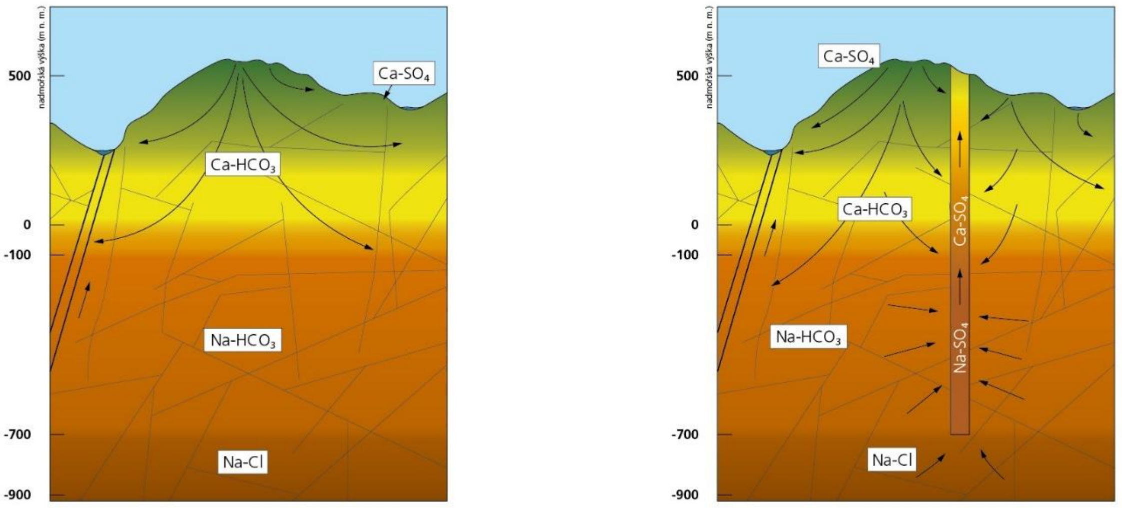

Fig. 8 – Scheme of the development of the chemical composition and flow of groundwater with depth left: in a crystalline rock environment without anthropogenic intervention, right: in a crystalline rock environment affected by the mine (Bukovská et al. 2017)

4.2 EDZ I (2015-2018)

Project name: Creation and monitoring of EDZ during the construction of the Bukov URF

Participants: Institute of Geonics, Academy of Sciences of the Czech Republic; Geotest a.s.

Links to the DGR programme

When excavating the underground areas of the DGR, especially the disposal corridors, it will be necessary to verify the properties and extent of the excavation damaged and influenced zones in the vicinity of the underground corridors (EDZ and EIZ). It will be necessary to apply reliable and proven methods, which are currently still in the development phase.

Objectives

- The acquisition of data related to the creation and development of excavation damaged zones (EDZ) and influenced zones (EIZ) around the underground workings and the rock archways during the construction of the laboratory corridors.
- The application of various methods for determining the extents of the EDZ/EIZ and their comparison with respect to the corridors excavated via the normal blasting procedure and those excavated via the smooth blasting method.
- The monitoring of changes in the stress in the rock in the redistributed stress areas in the vicinity of the corridors.
- The creation of a 3D model of the laboratory spaces using laser scanning data and a mathematical model of the stress field.

Research approach

- The repetition of electrical resistivity tomography and seismic measurement campaigns on selected profiles on the walls of the laboratory corridors for the interpretation of potential changes in the parameters of the EDZ/EIZ over time.

- The determination of the principal stress values applying the CCBO method and the long-term monitoring of stress changes in the rock using the compact conical ended borehole (CCBM) method on boreholes drilled in advance and guided in the direction of the excavation of laboratory corridors in a fan arrangement. The monitoring of stress changes during the excavation process at various distances perpendicular to the laboratory corridors (Fig. 9).

Results

- The project included extensive research with a summary of the findings on the creation and development of EDZ in crystalline rocks (Vavro et al. 2016).
- The results of the geophysical measurements revealed the area that can be interpreted as the EIZ. The limit was detected at a distance of 0.75 to 1.50 m from the walls of the corridors excavated via the smooth blasting method and up to around 5 m from the walls for the main access corridor excavated via the conventional blasting method. Fig. 10 shows the results of the comparison of the repeated ERT measurements in the ZK-1 corridor and the interpretation of the influence in the area.
- The experience obtained confirmed the high degree of difficulty of obtaining data for the interpretation of the EDZ in anisotropic rocks. It is necessary to apply a broad range of methods in order to accurately determine the extent of the EDZ.
- The results of the measurements applying the CCBO method indicated the relatively large dispersion of values in terms of both the magnitudes of the main components and their orientation. The interpretation of the measurements confirmed the influence of both excavation in the area and nearby fault zones.
- The CCBM monitoring results demonstrated the predicted response to the progress of the excavation work; the most significant changes in the stress were recorded by the probes positioned closest to the walls of the corridors. Long-term monitoring indicated that the gradual redistribution of stress occurs even following the end of active intervention in the rock mass (up to one year).

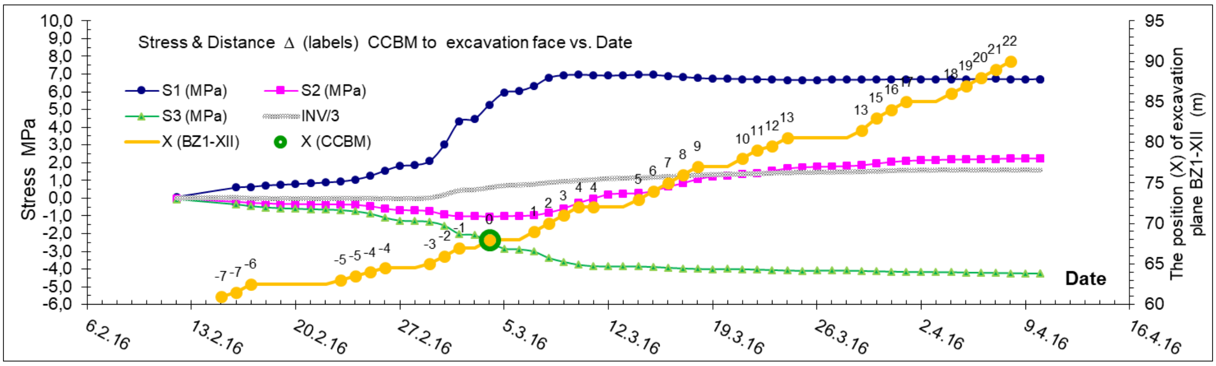

Fig. 9 – Example of the course of the calculated stress changes related to the time and progress of the excavation of corridor BZ1-XII (Staš et al. 2019)

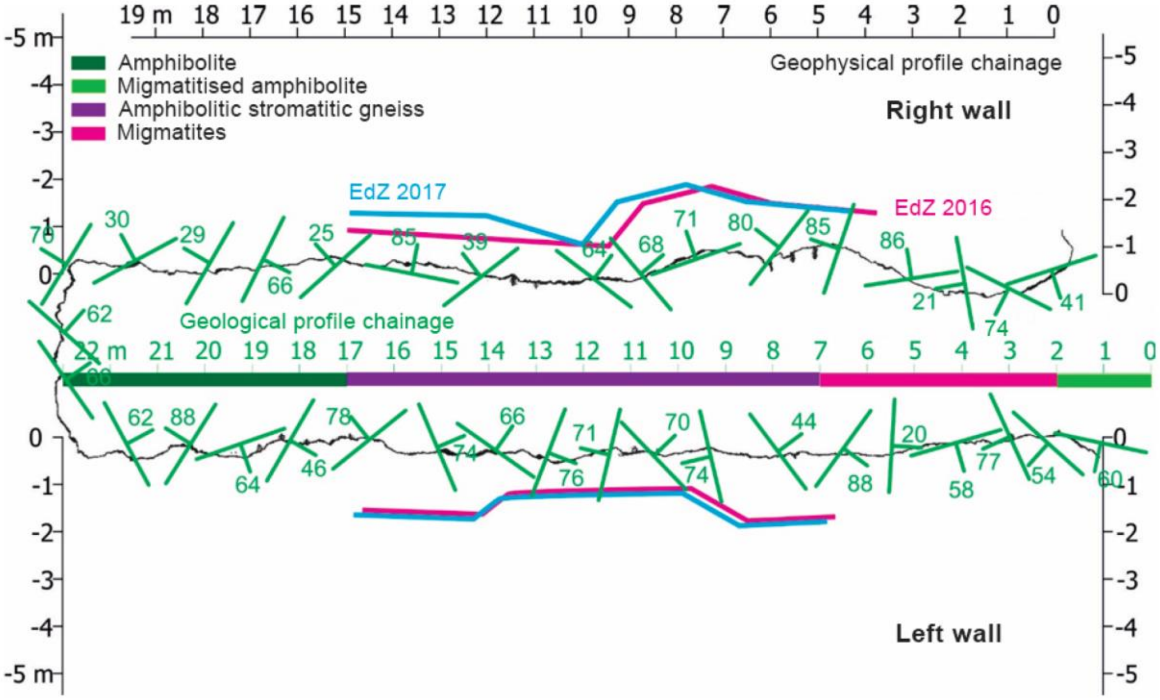

Fig. 10 – Interpretation of the EdZ and its development in the period 2016-2017 from ERT measurements taken in the ZK-1 corridor (Staš et al. 2019)

4.3 Microbiology I (2017–2019)

Project name: Microbial screening of the Bukov URF and Rožná mine

Participants: Technical University of Liberec - Institute of Nanomaterials, Advanced Technologies and Innovation

Links to the DGR programme

The currently considered DGR engineered barriers may be influenced by microbial activity (microbes present in the rock environment and/or in the bentonite sealing barrier). In order to evaluate the safety of the technical design solution of the DGR, it will be necessary to determine the influence of microbial settlement on the stability of the engineered barriers, prior to which it will be necessary to determine methodologies for the detection of the presence of target groups of microorganisms in the rock environment and/or in the engineered barriers and for the monitoring of the development thereof.

Objectives

- The conducting of pilot sampling campaigns in the Bukov URF and other parts of the Rožná I mine so as to determine the functional diversity of the microbial communities.
- The acquisition of data for planned experiments concerning the research of the corrosion behaviour of the engineered barrier materials.
- The drawing up of a long-term microbial monitoring plan.

Research approach

- The collection and analysis of water samples and microbial growth on the rock from levels 12 (in the Bukov URF area and further afield) and 24 of the mine.
- The application of molecular biological methods (the amplicon sequencing of the 16S rRNA region and qPCR) and cultivation procedures so as to determine the microbial diversity.
- The design of a system with a passive sampler for the collection of microbial biomass from water outflowing from boreholes (Fig. 11).
- The monitoring of the hydrochemical parameters of the water.

Results

- The microbial diversity in the studied area is influenced significantly by the aerobic environment of the mine corridors.
- The most abundantly represented functional groups include microorganisms capable of oxidising organic substances and iron and sulphur compounds.
- Obligate anaerobic microorganisms were detected only in small quantities; mainly groups that are capable of oxidising organic substances, iron and sulphur compounds were detected.
- The microbial diversity in the water in the studied boreholes remained relatively stable over the monitored period (1 year).
- From the point of view of research into the stability of the engineered barriers, it was recommended to continue monitoring the network of measuring points so as to ensure the comprehensive characterisation of those anaerobic microorganisms that were not fully described in the screening process.

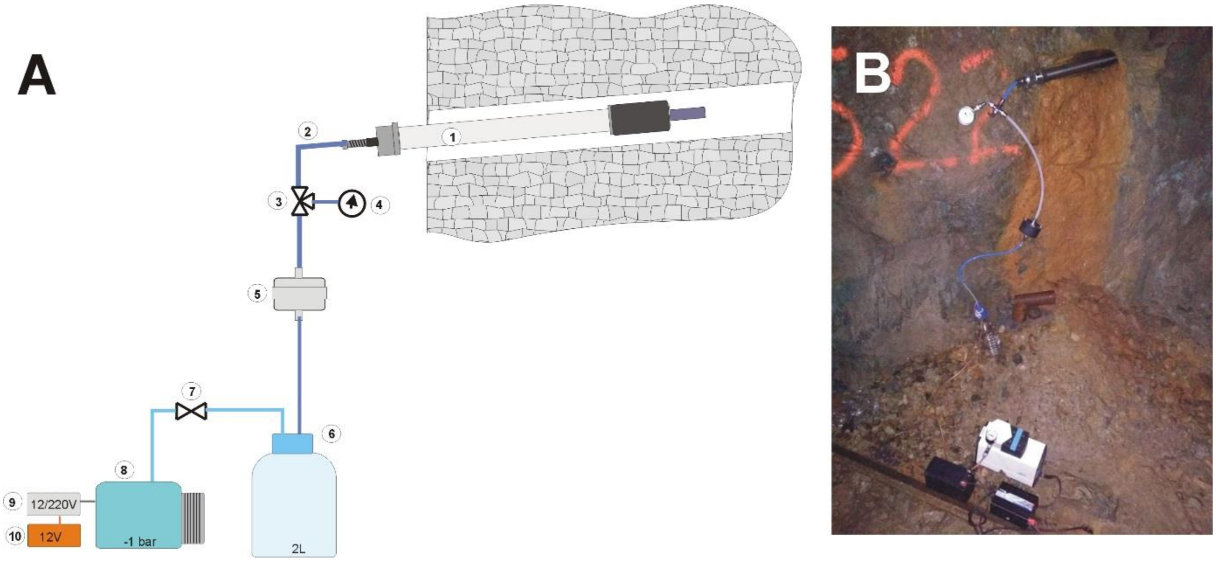

Fig. 11 – The system used for taking microbiological samples from the groundwater

4.4 Deep horizons (2017–2020)

Project name: Acquisition of data from the deep horizons of the Rožná mine

Participants: Czech Geological Survey (project coordinator); ÚJV Řež, a.s.; Institute of Geonics AS CR, v.v.i.; Masaryk University, SG Geotechnika, a.s.; INSET, s.r.o.; DIAMO, s.p.

Links to the DGR programme

The underground spaces, especially the disposal corridors, of the DGR must not be traversed by large-scale fault zones since they may provide direct pathways for the transport of radionuclides from the disposal site into the geosphere and further into the biosphere. The Rožná I mine provided a unique opportunity to study such fault zones/structures at various depths, specifically zone 1 (R1) of the uranium deposit (the main ore-bearing structure), which comprises a tectonic zone with a thickness of up to 20 metres that is accessible from corridors at depths of 550 to 1200 m (levels 12 - 24 of the mine).

Objectives

- The description of a large-scale fracture/fault zone as a structure that must not feature in the immediate vicinity of the disposal spaces in the DGR rock mass, which is key to the safety of the facility.
- The obtaining of information on the spatial distribution of the geological and geotechnical properties of the rock environment at different depths in the Rožná I mine (Fig. 12).
- The obtaining of information on the geochemical and transport properties of the rock.
- The definition of how and to what distances from large-scale fault zones the properties of the rock mass are affected.
- The expansion of the existing database of knowledge on the local rock environment and thus the scientific potential of the underground laboratory.
- The interpretation of changes in the geological parameters with depth and the gathering of the reliable information from the crystalline rock environment of the Bohemian Massif required for the DGR development programme.

Research approach

- The study of the properties of the R1 fault zone at various depths.
- The preparation of geotechnical stations equipped with exploratory boreholes at various levels of the mine, specifically on levels 12, 18, 20, 21, 22 and 24 near to the R1 zone.
- The application of various methods for the determination of the structural, geomechanical and geochemical parameters of the rock at various distances from the R1 zone.
- The assessment and reinterpretation of archive geological and tectonic knowledge of the site, the structural documentation of the fracture network components, the creation of a DFN (Discrete Fracture Network) model, ERT and seismic measurements on the surfaces of corridor walls and in boreholes, the determination of in-situ stress, the study of EDZ/EdZ and the laboratory testing of rock samples.

Results

- In addition to classic structural documentation, data obtained from photogrammetric models of the corridor walls were used to obtain data for the creation of the DFN models. A comparison of the two approaches demonstrated that data provided by photogrammetric models can be used in the study of the intensity of fracturing and to construct reliable DFN models.

- The applied methods did not reveal a correlation between the mechanical properties of the rocks and depth below the surface. Since the heterogeneity of the rocks was more pronounced than the potential influence of the presence of the R1 zone, no trend was detected concerning changes in the mechanical properties of the rocks with distance from this zone.
- A particularly important finding concerned the fact that the presence of zone R1 has influenced the intensity of fracturing and the total number of fractures in the rock in the wider vicinity thereof. The transition area (between the fault zone and the unaffected rock), featuring an enhanced intensity of fracturing, evinces a range of several tens of metres and its strength in certain cases exceeds the strength of the R1 zone itself by several times.

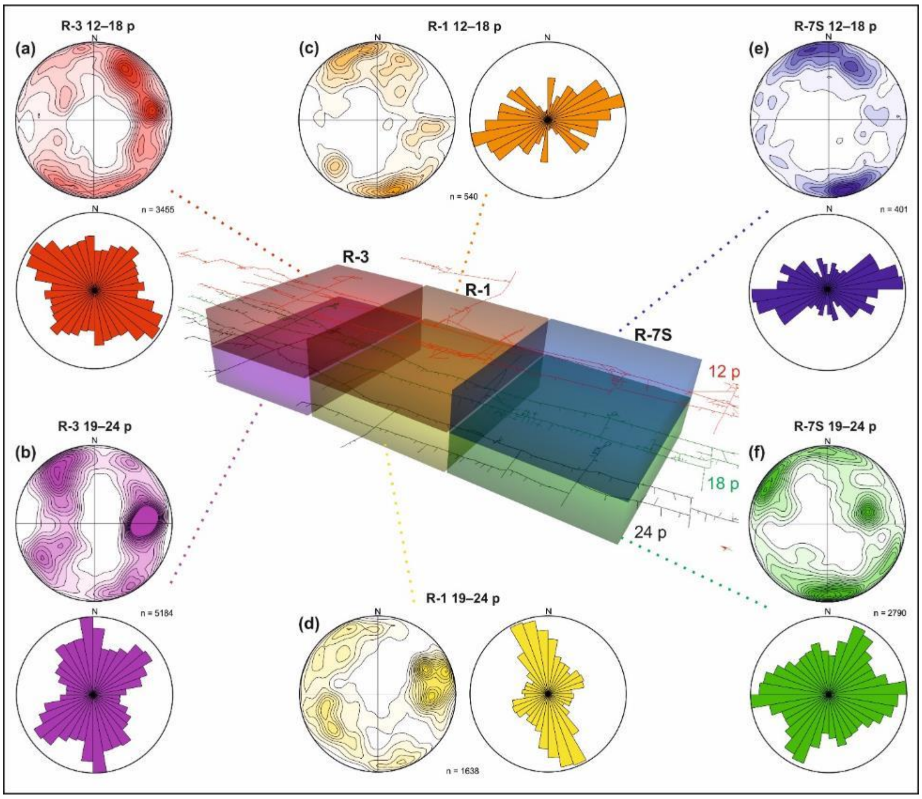

Fig. 12 – Structural diagrams illustrating the spatial changes in the orientation of the brittle structures in the whole of the studied area of the Rožná I mine (Bukovská et al. 2020)

4.5 Hydromonitoring I (2018–2023)

Project name: Hydrogeological and hydrochemical monitoring of underground and mine water in the Bukov URF

Participants: Geotest, a.s.; KOCMAN Envimonitoring s.r.o.

Links to the DGR programme

The hydrogeological properties of the rock mass and the hydrochemical properties of the groundwater are key to the safety of the DGR. The Rožná I mine and the Bukov URF provide a unique opportunity for the study of the properties of a crystalline rock mass at various depths applying methods for which direct access to the rock from an open underground space is necessary. The age of some of the mine workings (several decades) also allows for the determination of how the hydrogeological and hydrochemical properties were affected by the long-term operation of the mine.

Objectives

- To form an understanding of the nature of the flow of shallow and deep circulation groundwater.
- The continuation of long-term monitoring along the network of monitoring points created during the construction of the Bukov URF I in 2015. The replacement of non-functional monitoring points and the addition of new points.
- The evaluation of the development of the chemistry of the water that flows into the underground workings and the development of the yields of such inflows.
- The evaluation of the parameters on the surface of the site.

Research approach

- The online monitoring and interpretation of groundwater inflows to the Bukov URF I (from open boreholes, fracture systems). The measurement of inflows from fracture systems on the walls of corridors by diverting water into troughs and other equipment, the measurement of outflows from boreholes using flowmeters and the measurement of the total outflow from the Bukov URF I using a Parshall flume.
- The repeated sampling of the groundwater for the analysis of changes in its chemistry. Analysis aimed at determining the age of the water. Sampling along a network of points located within and accessible from mine workings beyond the laboratory area on level 12 (as well as in the deeper parts of the mine to level 24 at a depth of 1200 m (up to 2020)).
- The monitoring of the parameters of the water along a network of observation points on the surface above the Bukov URF and in its wider surroundings.

Results

- The monitored inflows of water to the laboratory area evinced only minor seasonal fluctuations. Overall, most of the inflows have displayed a gradual declining trend since the commencement of monitoring (Fig. 13).
- Underground hydrochemical monitoring was conducted quarterly at a total of 15 locations and included the basic analysis of the water, the measurement of the concentrations of trace elements and the determination of radioactive substances in the water. Concerning the laboratory complex, the Ca-Mg-HCO_3-SO_4 water type prevails (the predominant anions in the water comprise mainly bicarbonates; sulphates prevail only occasionally and this was not found to result in any fundamental changes in the water chemistry) and type Ca-Mg-HCO_3 water. The groundwater at the site is predominantly of the Ca-SO_4 type.
- The age of the groundwater was determined using several independent methods. The method applied for determining the retention time of the water in the rock environment based on the determination of tritium proved that the water in the Bukov URF environment mixes only to a limited extent with rainwater, a minimum amount of which seeps into the underground complex. The freon degradation measurement method failed to yield any relevant results. The determination of the age of the water, i.e. the retention time of the water in the rock environment, using the radiocarbon method (the

measurement of the ^{14}C isotope) showed that the water in the proximity of the Bk26 inflow is approximately 5000 years old, i.e. its retention time. Similar methods were also applied in the Characterisation I project (Bukovská et. al 2017). The age of the water (retention) according to the ^{14}C radiocarbon dating method was determined at approximately 7000 years. According to the location in which the water samples were taken, the project determined the age of the water as between 6000 and 9000 years.

- It was determined that Na-HCO$_3$ and Na-SO$_4$ types of water predominate in the deeper parts of the Rožná I mine (levels 12 to 24). The research in this part of the mine also included the determination of the detailed elemental composition of the groundwater. The mineralisation for the Ca-Mg-HCO$_3$-SO$_4$ type water was determined at 0.3-1 g/l.
- Differences in the pH of the groundwater were observed at the various levels. The water on level 12 was found to be slightly alkaline, with pH values of between 7.5 and 8.1. The water evinced a neutral pH of 7 in the shallower parts, whereas the water evinced a pH of 10 on the deepest levels of the mine. Thus, the pH value increases with increasing sampling depths.
- The radiological analysis of the groundwater determined that the limit set out in Decree No. 422/2016 was not exceeded during the monitoring period. Only slight excesses of the total volume alpha activity were measured at points Bk23, Bk06, Bk26 and Bk35, which, however, did not continue throughout the monitoring period, i.e. isolated slight increases in activity, after which the values returned to normal. The only inflow at which a significant increase in activity was observed concerned point Bk27, which evinced enhanced radon activity throughout the monitoring period.

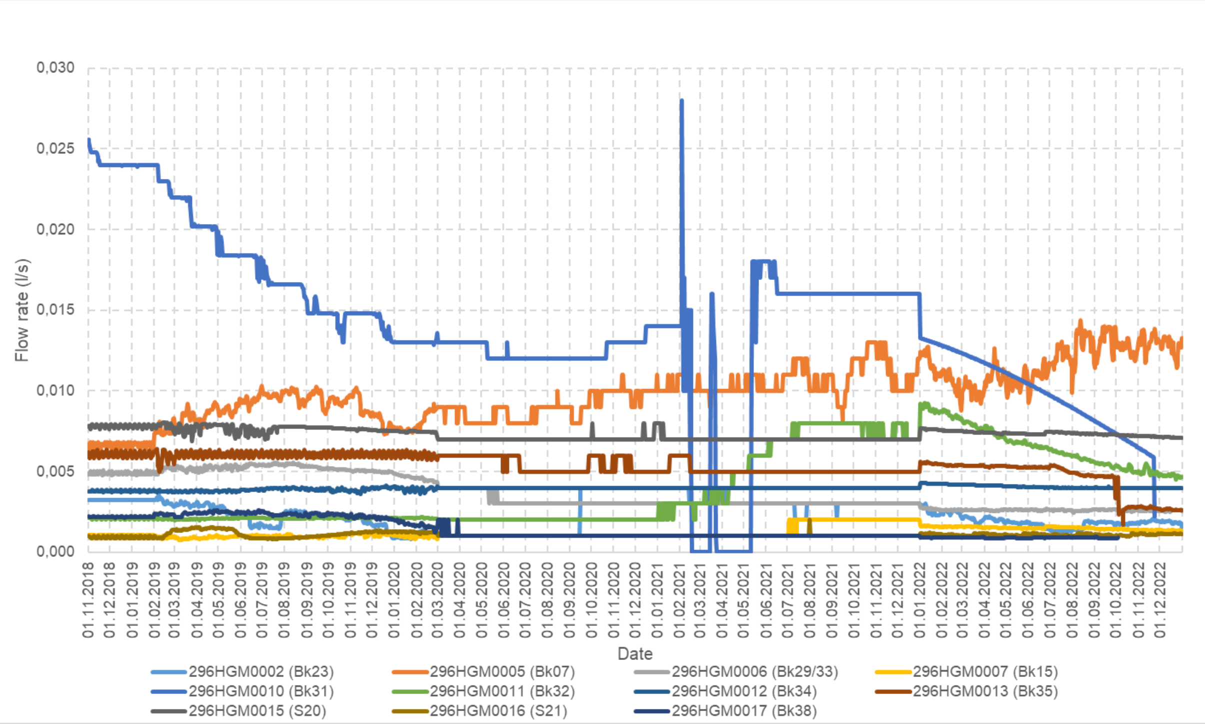

Fig. 13 – Yields of the underground inflow points in the Bukov URF (Vylamová et al. 2023)

4.6 Non-destructive geophysics (2018–2022)

Project name: Long-term monitoring of the rock mass in the Bukov URF using non-destructive geophysical methods

Participants: Technical University of Liberec/Institute for Nanomaterials, Advanced Technologies and innovation, G IMPULS, s.r.o.

Links to the DGR programme

Non-destructive geophysical methods provide valuable information on the properties and behaviour of rock masses, including the EDZ/EIZ, without the need for borehole drilling. Concerning the DGR, it is assumed that non-invasive methods will be applied to the greatest possible extent so as to ensure the minimum disturbance of the host rock environment. Although these methods have made significant progress in recent years, they are still in the development phase.

Objectives

- The design, installation and operation of an electrical resistivity tomography (ERT) system and seismic measurements along the walls of selected laboratory corridors.
- The long-term monitoring of changes in the properties of the selected rock block initiated as a result of natural development or other activities at the site (e.g. drilling work, water pressure testing, etc.).

Research approach

- The use of a combined geophysical measurement system developed and tested in the Bedřichov tunnel.
- The taking of pilot parametric seismic and electrical resistivity tomography measurements along the walls of the laboratory corridors applying various spacings of the geophones and electrodes aimed at the design of the arrangement of instrumentation for long-term monitoring purposes.
- The installation and operation of the SGI 1 (Seismics, Geoelectrics, Internet, version 1) system, which combines ERT measurements along a series of electrodes and seismic measurements using geophones, on the left wall of corridor BZ1-XII, (Fig. 14).

Results

- The long-term monitoring system was put into operation in September 2019, whereupon the monitoring phase commenced aimed at the monitoring of changes in the properties of the rock block of interest.
- Prior to installing the measurement system, it was necessary to make the necessary modifications and to prepare the system for the taking of measurements at the Bukov URF. The SGI 1 measuring system was originally tested in the Bedřichov tunnel, where the rock environment is both homogeneous and compact. However, the rock in the Bukov URF exhibits elevated fracturing and a significant number of microfractures, which negatively affected the transmission signal, especially when measuring active seismicity.
- The project included the measurement of active seismicity using the SGI 1 system (measurement applying seismic radiation through rock). Releasing of seismic signal

was applied several times daily and the data collected required careful analysis. The results of the measurement campaigns revealed that changes in the seismic signal amplitudes were more pronounced than changes in the velocity in the environment in which changes in its properties occurred.

- The monitoring of the passive seismicity initially evinced a low degree of sensitivity to seismic events. At the end of the project, however, the opposite trend was observed, i.e. the set sensitivity of the device led to continuous signal registration. This development was due to the inaccurate registration of the signal sent by the equipment for the monitoring of the water exiting the rock, during which time the localisation of seismic events was not tested due to the locations of the sensors.
- The electrical resistivity tomography measurements allowed for the investigation and monitoring of the resistivity profile of the selected site, thus enabling the determination of the expected rate of apparent resistivity? changes. Changes were observed in the specific resistivity values due to the weekly ventilation cycle in the Bukov URF. The maxima were observed on Sundays when the URF is not ventilated. Ventilation exerted a similar impact on the measurements taken using the seismic method, according to which the signal maxima were mostly observed on Fridays, while minima were observed on Sundays. These changes were explained by the condensation of water that occurs when the ventilation system is switched on. The water connects those fractures that would otherwise not be connected. In the absence of ventilation, the water begins to evaporate, which leads to increases in the electrical resistivity measured in the rock mass. The fact that the ventilation cycle exerts an impact on the Bukov URF environment was also indicated by the active seismic measurements.
- The results indicated that it would be appropriate to continue the recording of measurements of this type and to supplement them with measurements using radar, stimulated polarisation and the determination of stray currents.

Fig. 14 – View of the experimental site (Bárta et al. 2022)

4.7 Brittle structures (2018–2022)

Project name: Monitoring of the activity of brittle structures in the Bukov URF and the Rožná mine

Participant: Institute of Rock Structure and Mechanics (ÚSMH) AS CR

Links to the DGR programme

In order to prove the tectonic stability of the DGR host rock formation, it will be necessary to select a suitable method for the verification of movements along tectonic structures. Many years of experience have been obtained in this respect in the Czech Republic from gauge networks that provide data for the interpretation of the tectonic behaviour of the Bohemian Massif.

Objectives

- To obtain knowledge on the movements of brittle structures in crystalline rocks at a depth corresponding to that of the future DGR.
- The construction of a monitoring network that will provide time series data on the behaviour of various generations of brittle tectonic structures at a range of scales (fault zones, faults, fracture zones, fractures).
- To determine a general interpretation of the movements of the structures monitored in the Bukov URF and to construct a mathematical model for the simulation thereof.

Research approach

- The measurement of the movements of brittle structures involves the use of TM-71 3D optical-mechanical extensometers (dilatometers). This device, which was developed by the ÚSMH, features a very high resolution compared to traditional or even more modern techniques for the monitoring of slow movements in rock masses. The device is able to record displacement in all three directions as well as in rotation with an accuracy of up to 0.001 mm. The device makes use of the optical interference phenomenon, which involves the monitoring and interpretation of the mutual displacements of the spirals on a pair of overlapping glass slides.
- The installation of extensometers on 10 selected structures with various orientations to the main directions of the in-situ stresses. Monitoring and maintaining the network so as to obtain the longest possible data series.
- The compilation of a “quasi-2D” model of the Bukov URF that considers a 3D horizontal section in the vicinity of the Bukov URF at a level of between approx. -563.5 m and -546.5 m with the inclusion of tectonic zones in the model in the form of zones of weakness. Simulation applying Plaxis 3D VIP software with the application of horizontal pressures on individual rock blocks and the reverse analysis of the measured movements.

Results

- The original network of measurement points installed in 2019 covered seven installed structures in the Bukov URF I complex, two structures on level 24 and one on level 20 of the mine. Information was collected from the measurement points installed in the structures on the lower levels of the mine up to mid-2020 when the equipment was dismantled due to the planned flooding of these levels. These devices were then remounted on three newly-selected structures within the laboratory area.

- The measurement network currently monitors 10 structures; all the meters are connected to the data network and the transmission of data is ongoing.
- The monitored period included an extension phase characterised by subsidence and the opening of the monitored brittle structures, a period without any significant shifts and, subsequently, a period of compression (Fig. 15).
- In general, the displacements in the monitored structures vary in the range of hundredths of mm per year and have either a short-term or pulse-like character.
- The modelling provided information on the stress and pressure conditions in the area and an interpretation of the faulting of the area in the form of tectonic lines. The model provided a rough prediction of directional displacements in which the predictions correspond qualitatively very well to the measurements and quantitatively correspond to the respective order of magnitude.

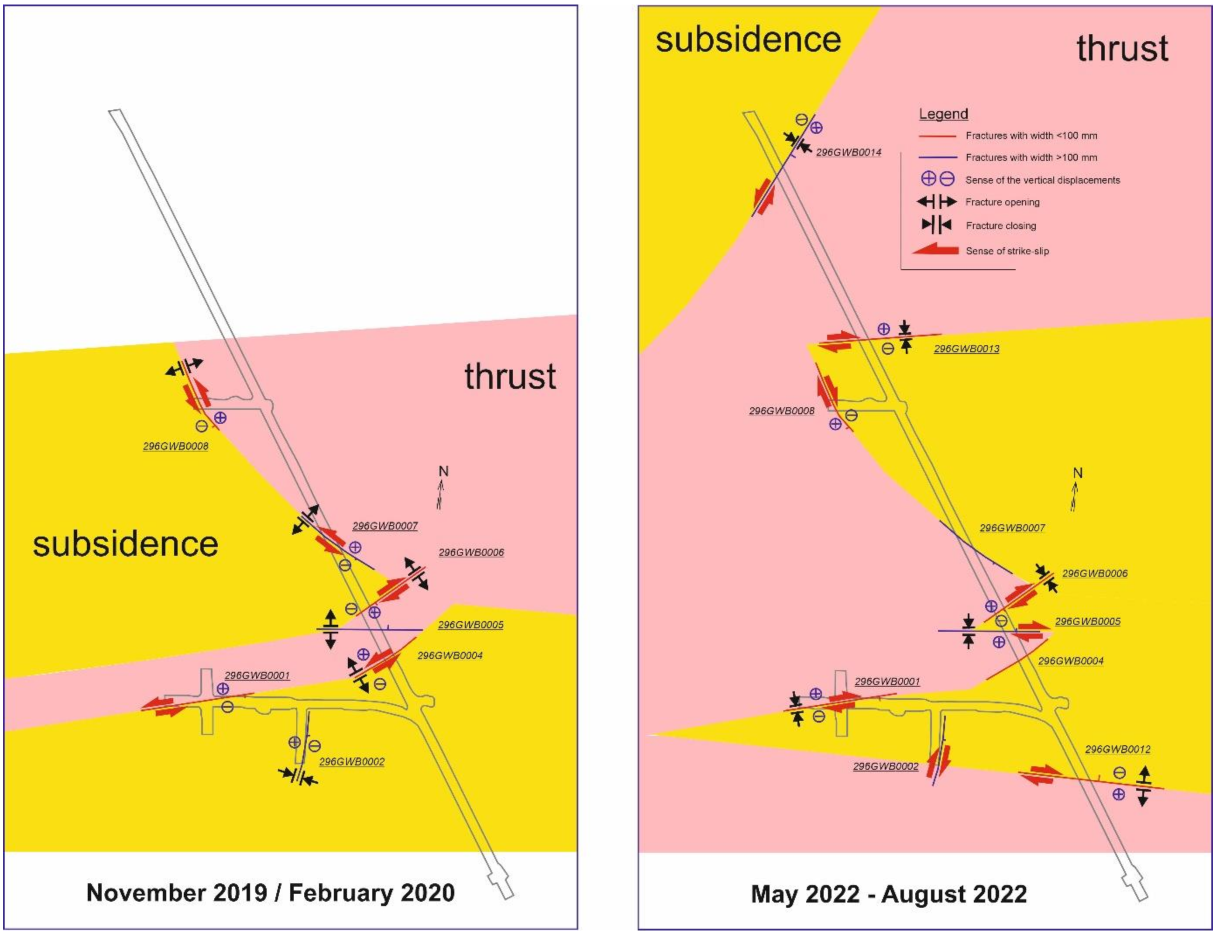

Fig. 15 – Comparison of vertical movements between two significant periods (Stemberk et al. 2022)

4.8 Microbiology II (2020–2021)

Project name: Monitoring of anaerobic microbial settlement in the Bukov URF and research into the links between the rock environment and microbes

Participant: Technical University of Liberec/Institute for Nanomaterials, Advanced Technologies and innovation

Links to the DGR programme

This project followed up on the microbial screening campaigns conducted between 2017 and 2019 (chapter 4.3). The microbial population at the Bukov URF and in other parts of the Rožná I mine was characterised as being strongly anthropogenically influenced (primarily aerobic microbe representatives). The follow-up project focused particularly on anaerobic microbial activity, which had not previously been accurately described in the Bukov URF.

Objectives

- To improve the overall understanding of the differences between the natural microbial colonisation of rock environments and anthropogenically influenced environments.
- In-depth familiarisation with the microbial activity in the Bukov URF with regard to planned experiments (Corrosion experiment - chapter 5.4, etc.).
- The description of the connections and uncertainties surrounding microbial processes within the DGR system. The updating of the approach to microbial assessment in the DGR context.

Research approach

- The collection and analysis of water samples taken from flooded boreholes in the Bukov URF using a methodology tested in the context of a previous project. The determination of the microbial diversity applying molecular-biological approaches (DNA extraction, quantitative real-time PCR and Next generation sequencing).
- The parallel monitoring of the hydrochemical parameters of water that flows from boreholes (oxygen content, Eh, pH, temperature, conductivity) and the laboratory hydrochemical analysis of samples of the water.
- The interpretation of the development of microbial diversity at the monitored points. The calculation of the relative representation of the various populations of microorganisms and its comparison with data obtained from previous monitoring campaigns conducted in the Czech Republic focusing on the presence of potentially dangerous groups of microorganisms (sulphate-reducing, iron-reducing, iron-oxidizing, methanogenic and acetogenic microorganisms).
- Research that focuses on the microbial activity expected in the DGR from the point of view of anthropogenic microbe sources and microbes from unaffected rock. The comparison of the degree of influence of microbial activity from rock environment sources versus bentonite sources on the various components of the DGR. The determination of conclusions from the study of microbial activity and related processes including the corrosion of the WDP, bentonite illitisation and hydrogeochemical processes.

Results

- The microbiological analysis was supplemented by in-situ hydrochemical monitoring, which provided important information on the environmental conditions that determine the state and development of microbial communities (and thus act as reliable predictors of certain characteristics of the microbial settlement of deep-flowing groundwater).
- All the groups of dangerous microorganisms that will potentially be involved in microbially-induced corrosion in the DGR (mainly sulphate-reducing and sulphur-oxidising bacteria, iron-reducing and iron-oxidising bacteria and nitrate-reducing

bacteria) were detected, as were microorganisms that have the potential to influence the functional properties of bentonite (mainly iron-reducing bacteria).

- It was proven that the stability of the local environment and the non-availability of terminal electron acceptors comprise the key parameters in terms of minimising the microbial activity in the DGR.
- The results of a range of independent studies (Černá et al. 2021) have demonstrated that the degree of microbial diversity varies significantly between rock samples and between the type of groundwater (even if the samples are extracted from the same place). In addition, it is known that several orders of magnitude more sessile microorganisms are present than planktonic microorganisms. Therefore, groundwater samplers are not ideal for the study of sessile microorganisms, the composition of which is, in most cases, fundamentally different from that of planktonic microorganisms.
- A further factor that significantly affects microbial diversity comprises the rock environment (e.g. pyrite, marcasite, calcite, etc.) and the related availability of terminal electron acceptors, electron donors and the availability of carbon sources (Fig. 16). An equally important factor concerns the depth and the degree of isolation (i.e. the extent to which the studied site is interconnected by fracture systems). A change in just one minor parameter is enough to dramatically change the microbial community.

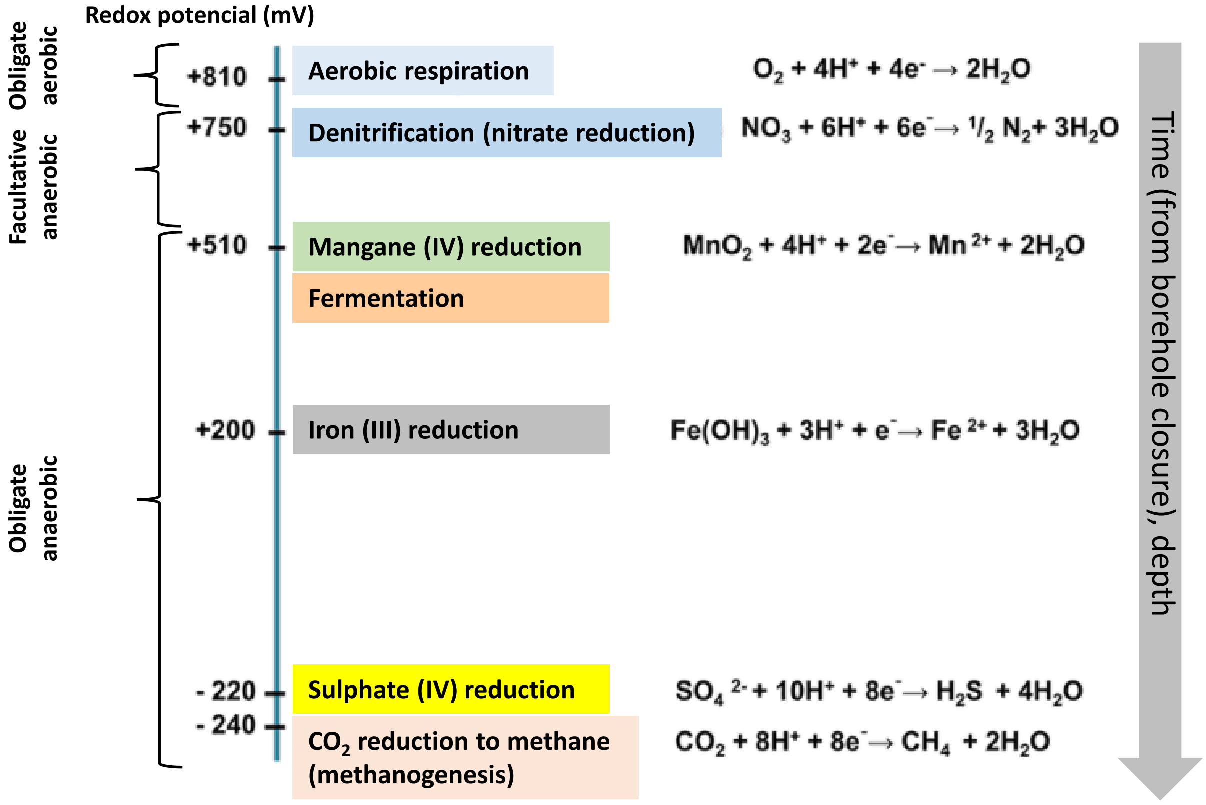

Fig. 16 - Sequence of reduction reactions and terminal electron acceptors (Steinová et al. 2021)

4.9 Seismic URF II (2020–2021)

Project name: Determination of the spatial homogeneity of the environment before carrying out blasting work using seismic tomography

Participant: INSET s.r.o.

Links to the DGR programme

The seismic tomography method indicates the quality of the rock mass by measuring the velocity of the propagation of seismic waves. It allows for the determination of the degree of rock failure and the identification of fault zones and EDZ. With respect to the DGR, this method will be particularly suitable for identifying stable, non-fractured rock blocks and for assessing the geomechanical properties of the rock.

Objectives

- The creation of a seismic map of the rock block intended for the excavation of the Bukov URF II corridor complex by taking measurements in exploratory and pilot core boreholes of the laboratory corridors in the area of interest.
- The obtaining of data on the spatial distribution of rock failure zones and the determination of the degree of failure of the investigated rock block.

Research approach

- The application of seismic wave propagation measurement methods in a system of five boreholes in the Bukov URF II rock block. Measurements were taken between the boreholes and via sensors installed on the wall of access corridor PŠ1-123.
- The evaluation of the various measurements via the compilation of a map of the seismic velocities of the studied rock environment.

Results

- A map (
- Fig. 17) that covers the entire area of the future Bukov URF II complex, which will have dimensions of approx. 100 x 200 m.
- In general, the measurements indicated the relatively low degree of rock failure.
- The intact or weakly fractured rocks in the Bukov URF II environment usually exhibit a seismic velocity in excess of 5800 m/s.
- The project provided important data on the prediction of the development of lower quality (fracture zone) areas that can subsequently be compared with the information obtained via the monitoring of the walls of the Bukov URF II corridors.
- The results predicted the development of a weakened rock zone, which was subsequently confirmed during the excavation of the laboratory corridors, which featured higher groundwater inflows (
- Fig. 17).

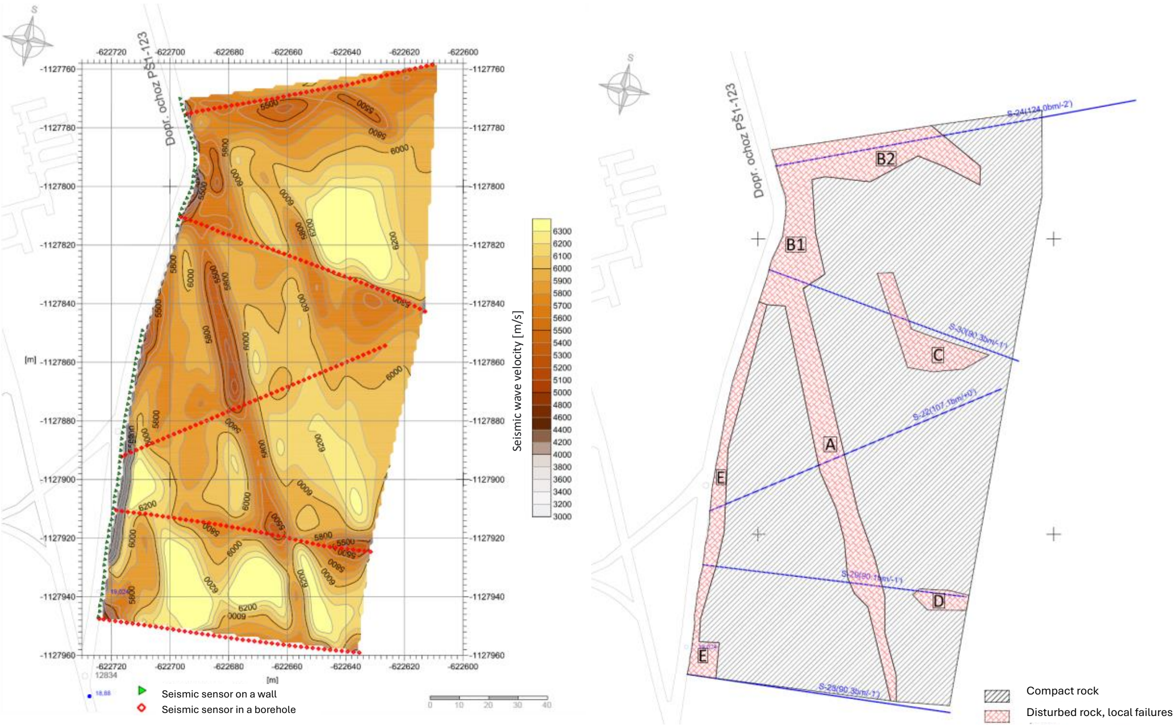

Fig. 17 – Left: the results of the tomographic processing of the velocity field; right: a block interpretation diagram (Chabr et al. 2021)

4.10 POSIVA FLOW LOG (2022)

Project name: Utilisation of POSIVA experience in the application of Posiva Flow Log (PFL) – Posiva Flow Log measurements in four boreholes at the Bukov underground research facility in the Czech Republic

Participant: Posiva Solutions

Links to the DGR programme

In order to obtain information on the hydraulic conductivity of the DGR host rock, it will be necessary to use equipment and methodologies that have been thoroughly tested and verified. In this respect, SÚRAO made full use of the unique opportunity to obtain comparative data from the Posiva Flow Log (PFL) device, which was specially developed for the environment of crystalline rocks that feature very low hydraulic conductivity and fracture permeability. The device is capable of detecting inflows into boreholes from small-scale fractures with the aim of obtaining data for the determination of hydraulic conductivity, and allows for direct sampling for the chemical analysis of water collected from deep boreholes. The first experience of the application of this technique in the Czech Republic was gained in 2019 at the Melechov site (Komulainen et al. 2019).

Objectives

- The implementation and evaluation of a series of measurements in 4 selected boreholes in the Bukov URF.
- The localisation of permeable fractures within the test boreholes and the determination of the water yields of the fractures.
- The determination of the groundwater pore pressure and hydraulic conductivity of selected sections of the boreholes or in individual fractures.
- The extraction of groundwater from selected structures in the boreholes.

Research approach

- The taking of measurements in two sub-horizontal boreholes (S-33 and S-24), an inclined borehole (L8-54DL) and a vertical borehole (L7-87D) (borehole lengths of 30.3 - 124 m).
- The taking of measurements in boreholes under natural pressure conditions in the boreholes (open boreholes) and under enhanced water pressure conditions in packed boreholes (pressure of 2 MPa).
- The application of the “PFL DIFF” method (Posiva Flow Log Difference Flow Method) for the identification of water inflows to packed borehole sections and the direct measurement of the water parameters (electrical conductivity and resistance, temperature and the water pressure in the borehole).

Results

- A total of 43 hydraulically conductive fractures with water inflows were detected in three of the measured boreholes (S-33, S-24, L8-54DL). Concerning all three boreholes, a slightly higher number of water-bearing fractures were detected during the phase in which the water pressure was increased in the borehole. The largest number of hydraulically conductive fractures was recorded for borehole S-33 (16 fractures in the open borehole, 20 fractures at a pressure of 2 MPa).

- No water-bearing fractures were detected in the L7-87D borehole.
- The measurement of the pore water pressure in the fractures evinced lower values than expected given the depth below the surface.
- The transmissivity values of the measured borehole stages ranged from $3 \cdot 10^{-11}$ m/s^2 to $3 \cdot 10^{-8}$ m/s^2.
- The in-situ measurement was performed of selected chemical parameters (pH, oxidation-reduction potential (ORP), temperature, total concentration of dissolved substances). In borehole S-33, the pH values ranged between 8.1 - 9.0, i.e. relatively basic. The ORP in borehole S-33 was determined at between 207 - 279 mV. The temperature in this borehole varied between 15.0 - 15.8°C and the total dissolved solid (TDS) values ranged between 506 - 728 mg/l.
- The sampling of the water for laboratory analysis purposes was carried out from the S-33 borehole at a depth of 31.2 m. The analysis included the determination of the chemical composition of the water (anions, cations), specific conductivity (at 25°C), chemical consumption of oxygen, total organically bound carbon (TOC) and water activity (total beta activity and radon/radium in Bq/l). It is recommended that this data be compared with the results of the laboratory analysis of water samples from the boreholes.

Fig. 18 – Measuring stations at boreholes L7-87D and S-24

4.11 External projects

4.11.1 GEOSTAB (2017–2021)

Project name: Development of geotechnical and geophysical methods for obtaining 2D and 3D images of geological structures.

Participants: GEOtest, a.s.; Institute of Geonics AS CR; Technical University of Liberec / Institute for Nanomaterials, Advanced Technologies and Innovations

Links to the DGR programme

In a similar way to the project described in chapter 4.6., the key content of this project concerned the development and testing of non-invasive geophysical methods and geotechnical methods with a view to their future application in the DGR environment.

This was an external project conducted under the TRIO programme as supported by the Ministry of Industry and Trade (project no.: FV20294).

Objectives

- The development and testing of geophysical and geotechnical methods for the provision of information on geological structures in directions perpendicular and longitudinal to underground workings and their development over time.
- The definition of a comprehensive set of methods that will contribute to the more complete description of the geological structure of the rock mass in the vicinity of underground workings.
- The verification of measured geophysical values using data obtained via the application of various geotechnical methods.
- The compilation of algorithms for addressing 3D issues for geophysical resistivity and seismic measurements and the testing of programs for determining resistivity and longitudinal wave velocities in the vicinity of mine workings.

Research approach

- The taking of a series of geophysical measurements on the walls of underground workings, between boreholes and between boreholes and the surface of the underground working (ground and borehole radar, seismic tomography, electrical resistivity tomography and current radiation).
- The investigation of dependencies between the various physical and geotechnical properties of the rock mass and the development of software tools for the interpretation of experimental measurements. Subsequently, it is proposed that other, more established survey methods, will be applied to verify and interpret the results of the geophysical measurement campaigns.
- The use of several underground facilities with differing lithological and geomechanical conditions (Rožná I Mine – Bukov URF, Josef gallery, Modrá gallery).
- The key deliverables of the project, in addition to final and interim technical reports, include “proven technology” and software (GenieERT and GenieST).

Results

- The monitoring of the distribution of the physical properties in the wider vicinity of the Bukov URF determined that the bulk density, the specific resistance and the velocity of longitudinal waves do not differ significantly according to the lithological type; however, the magnitudes of the various parameters depend primarily on the mechanical condition of the rock.
- The assessed dependencies between the various physical and mechanical properties of the rock proved that a number of mathematical dependencies exist that can be applied in individual cases so as to determine the other important parameters of the rock. The research suggested that it is advisable to determine the properties of individual quasi-homogeneous blocks rather than those of the specific measurement locations.
- The application of current radiation showed that this method can only be used between boreholes and not between boreholes and mine workings due to the presence of steel reinforcement in the mine corridors.
- The results of measurements applying light geophysical methods indicated the presence of differences in the physical properties on the walls of the corridors that are not visible to the naked eye. This applies to both linear measurements along the walls and area measurements on selected surfaces.
- The borehole radar measurements provided a number of new findings concerning the surroundings of the measured boreholes, especially with respect to the radar radiation between the boreholes and the corridors.
- The results of the “geological” radar measurements provided very interesting information from behind the walls of the corridors. The aim of this method was to verify the origin of failure surfaces (anthropogenic or natural) and the quality of the rock environment (walls and the surrounding soil). It is necessary when taking such measurements to use an antenna with several frequencies since each frequency is able to provide information only within a certain depth range, i.e. a certain depth interface is displayed along with an indication of the various surface properties that reflect the given transmitted frequency. It is likely that the areas of discontinuity revealed by this method correspond to areas created by damage to the rock mass due to mining (EDZ).
- The project included the development of a procedure to extend the interpretation of ERT so as to be able to compile VES (vertical electrical sounding) curves from the ERT resistance measurements. The interpretation of the curves provided information on the geological structure behind the walls of the working. The degree of agreement in terms of the determination of the discontinuity areas between the ERT VES and radar methods was excellent.
- The 3D ERT measurements and their interpretation also provided insight into the stress distribution around the mine working. However, it is necessary to use interpretation tools that are able to process the results of measurements on electrodes located generally within the space. The results of these measurements in the ZK-1 corridor revealed the required types of information on the rock mass and its condition can be obtained via this approach (Fig. 19).

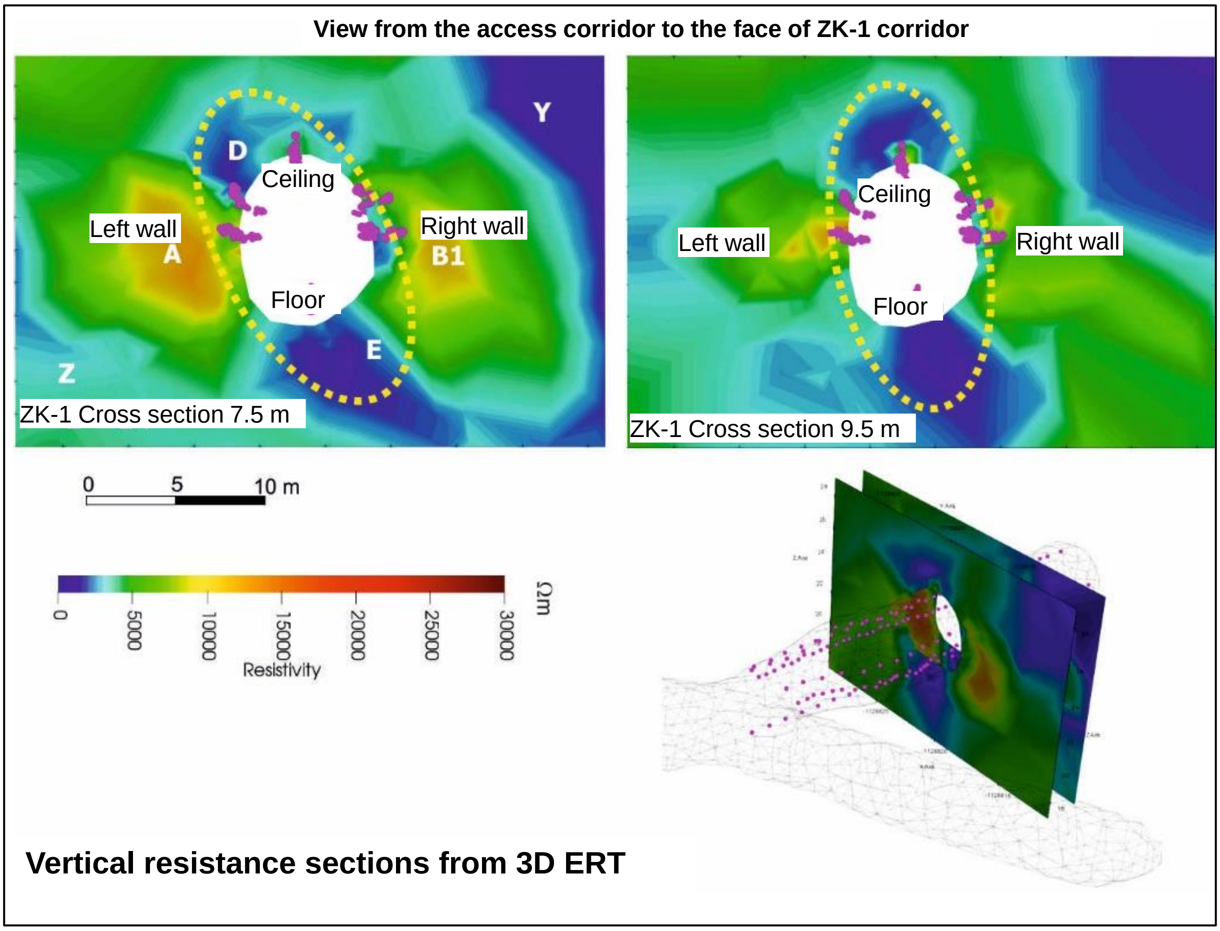

Fig. 19 – Vertical resistance sections through the ZK-1 corridor (Bláha et al. 2021)

4.11.2 GEOBARR (2018–2022)

Project name: Long-term research of geochemical barriers for nuclear waste disposal

Participants: Masaryk University Brno – principal researcher; DIAMO s.p. – co-investigator; SÚRAO – co-investigator without financial participation.

This was an external project conducted under the OPVVV programme as supported by the Ministry of Education, Youth and Sports (project no.: EF16_026/0008459).

Links to the DGR programme

The project was based on the natural analogue principle. Repositories for spent nuclear fuel (SNF) can, to some extent, be (conservatively) compared to natural uranium deposits, specifically uraninite and spent nuclear fuel. If the conditions that led to the formation of a uranium deposit in the earth's crust are determined, the conditions under which the uranium is or is not mobile within the natural environment can also be determined. When planning SNF repositories, it is necessary to avoid the conditions that may lead to the migration of radionuclides.

Objectives

- To supplement existing data on the mechanisms at work in the formation of uranium deposits and, in particular, the research of the characteristics of the surrounding geological environment that acted as a natural geochemical barrier to the migration of uranium from the Rožná uranium deposit to the surrounding area.

- Research into the assumption that the rock environment of the repository, which will be very similar to the rock environment of the uranium deposit, will act as a natural geochemical barrier and prevent the migration of uranium into the surroundings.

Research approach

- Research into the conditions of the primary accumulation of uranium at the Rožná deposit.
- Research into the conditions of the long-term stability of uranium at the Rožná deposit with regard to the use of the data obtained in research related to the DGR. This concerned primarily research into the long-term tectonic stability of the area, the geophysical detection of the main fault structures, the dating of rock exhumation using the *fission track* and *U-Th-He* methods, the dating of the age of the surface using cosmogenic isotopes and the seismic monitoring of the area.
- This external project made use of the opportunity to gain access to the Rožná mine and the archived data available on the uranium deposit.

Results

- The results of the project have been presented in a total of three reports published on the project's website (ÚGV MUNI, 2023), i.e. a pictorial report that presents selected results from the project on the behaviour and mobility of uranium during the formation of uranium deposits (2), a monograph on the history of the exploration of, and mining work conducted in, the Rožná uranium deposit (1) and educational reports that address uranium deposits (3).
- Publication (1), *"60 years of the mining of the Rožná uranium deposit",* provides a comprehensive summary of the knowledge obtained from the archived records made available by DIAMO - GEAM. The report describes a series of surveys of the area conducted prior to the start of mining operations, the mining processes employed and the geology and mineralogy of the deposit.
- Pictorial publication (2) *"Uranium Pathways"* presents pictorial evidence and the outputs of selected analysis of the GEOBARR project in the form of images with accompanying commentaries including examples of LA-ICP-MS (laser ablation inductively coupled plasma mass spectrometry) spectra and the BSE (backscattered electron microprobe) analysis.
- Publication (3) provides study materials for undergraduate students on the development of uranium deposits and their classification, and uranium mining in the Czech Republic.

5 Ongoing projects

This chapter provides information on ongoing projects, an overview of which is shown in Tab. 4.

Table 4 – Overview of ongoing SÚRAO projects at the Bukov URF

Name of project/contract	Working name of the project	Duration	Main area of the SÚRAO research programme	SÚRAO technical report (TZ)
In-situ interaction physical models in the Bukov URF	Interaction experiment	2017-2024	REP4	629/2022 (Svoboda et al. 2022b)
Investigation of the fracture connectivity in the Bukov URF	Fracture connectivity	2019-2024	REP3	630/2022 (Zuna et al. 2022)
Geological and geotechnical characterisation of the rock environment – Bukov URF II	Characterisation II	2021-2025	REP1	596/2022 (Bukovská et al. 2022)
Pilot corrosion experiment in the Bukov URF	Corrosion experiment	2021-2034	REP4	576/2022 (Dobrev et al. 2022)
Temperature monitoring of the rock mass in the Bukov URF and Rožná I mine	Temperature monitoring	2021-2025 (2030)	REP2	639/2022 (Dědeček et al. 2022)
EURAD - WP MAGIC	MAGIC	2021-2024	REP4	-
Determination of in-situ stress in the Bukov URF II	Stress	2023-2025 (2027)	REP2	-
Contour blasting work during the excavation of test chambers in the Bukov URF	Contour blasting	2023	REP6	-

5.1 Interaction experiment (2017–2024)

Project name: In-situ interaction physical models in the Bukov URF

Participants: CTU in Prague (Faculty of Civil Engineering), Czech Geological Survey; ÚJV Řež, a. s.

Links to the DGR programme

It is important to gain an understanding of the interactions between the various materials used in the construction of engineered barriers under the conditions expected in the DGR in order to determine their final design.

Objectives

- The verification of the properties of a bentonite sealing layer as affected by the presence of the rock environment and the groundwater and interactions with cement materials at elevated temperatures.
- The description and evaluation of the interactions between candidate materials for the engineered barriers of the Czech DGR, i.e. Czech Ca-Mg bentonite and concrete in an environment that corresponds to that of the DGR.
- The gathering of information and data for the mathematical modelling of the propagation of heat in the bentonite barrier and the host rock.

Research approach

- The design, construction and operation of physical models of DGR disposal wells. The experiment considers five unheated and five heated physical models (four models heated via electric heaters to 100°C and one to 200°C). The models, which were emplaced in horizontal boreholes (length 1.5 m, diameter 250 mm), contain bentonite fillings (compressed blocks segments or a granular mixture) and concrete segments (regular concrete and reduced-pH concrete).
- The models have been equipped with an artificial saturation system for the wetting of the bentonite filling with local groundwater and instrumentation for monitoring the development of the temperature and the bentonite saturation. In addition to the physical models, temperature sensors have also been installed in a series of boreholes drilled at various distances in the surrounding rock (Fig. 20).
- The loading phase (heating and saturation with water) and the monitoring phase of the physical models commenced in March 2019 and will continue until at least 2024. Following the conclusion of the operation of the models, they will be disassembled and samples of the materials in the models will be subjected to laboratory analysis.

Interim results

- Aimed at accelerating the interaction processes between the materials, the bentonite filling was artificially saturated with water under increased water pressure at the beginning of the experiment. The sensors in the bentonite recorded a rapid increase in the monitored parameters (moisture, swelling pressure) followed by their relative stabilisation as soon as after the first few weeks of the loading phase. The development of the parameters showed that the bentonite had become fully saturated as early as after the first few months.
- The measurement of the development and distribution of temperature in the models indicated the relatively rapid stabilisation of the temperature in the bentonite, followed by a gradual temperature increase in the surrounding rock.
- The project included the mathematical modelling of the experiment. The first stage of the modelling process served as support for the layout of the physical models in the laboratory test chamber and included the creation of models of the propagation of heat around the physical models. The second phase comprised the creation of a THM (thermo-hydro-mechanical) model of the behaviour of the physical models. The final stage consisted of the validation of the models using the data provided via monitoring and their application to interpret the behaviour of the experiment.
- Currently, the loading phase of the experiment continues with the ongoing saturation and heating of the models. The monitoring of the various parameters indicates their

long-term stabilisation. The short-term fluctuations in the measured parameters that have been observed were due to exceptional operational events (e.g. a power failure).

- The experiment is providing invaluable experience of the long-term operation of measuring systems.
- A follow-on dismantling project is planned for 2024, which will be based on the recommendations provided by Svoboda et al. (2022a).

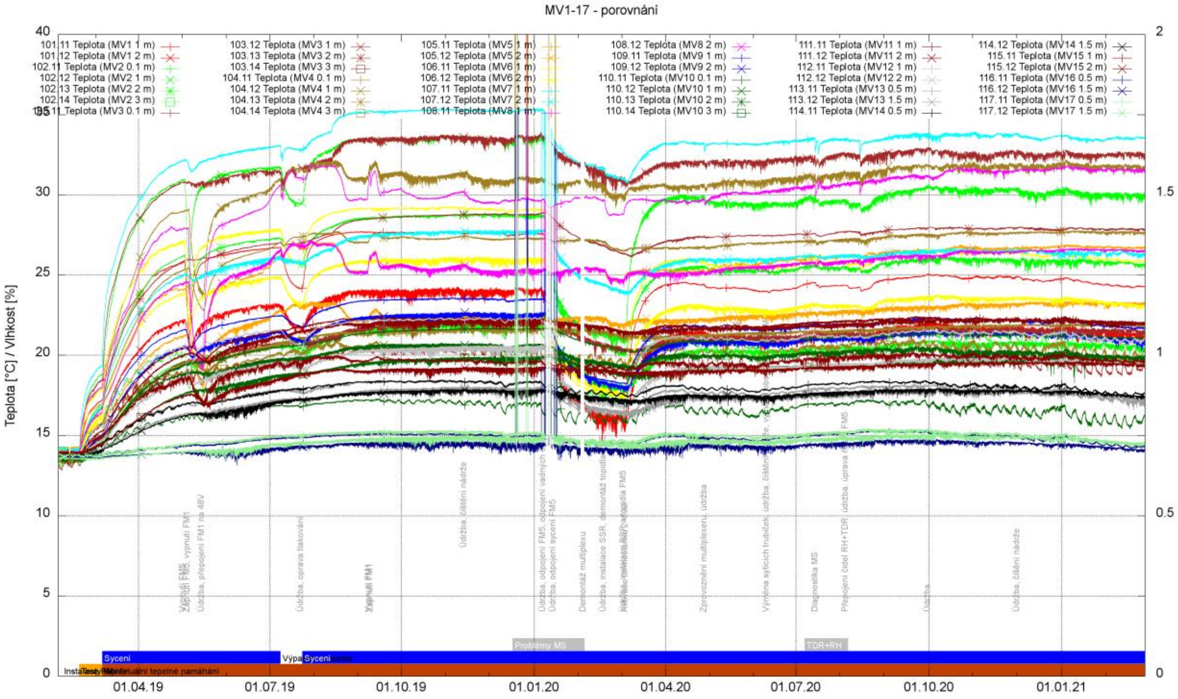

Fig. 20 – Example of the outputs of the monitoring of the temperatures at all the monitoring points in the rock surrounding the physical models (Svoboda et al. 2022b)

5.2 Fracture connectivity (2019–2024)

Project name: Investigation of the fracture connectivity in the Bukov URF

Participants: ÚJV Řež, a.s.; Czech Geological Survey; SG Geotechnika, a.s.; PROGEO s.r.o.

Links to the DGR programme

The main reason for the conducting of this project concerns the lack of information available on the hydraulic properties of the crystalline rocks of the Bohemian Massif at depths below the surface that correspond to those of the future DGR. The detailed description of the connectivity of fracture systems comprises one of the most important contributions to improving the overall understanding of the transport of radionuclides. With concern to the development and testing of the modelling tools that will be used to prove the safety of the DGR, it is necessary to obtain real data from the corresponding rock environment.

Objectives

- The acquisition of data for the creation of hydrogeological and transport models for the simulation of the flow of water and the associated transport of tracers.

- The geological and hydrogeological characterisation of the selected rock block (including the description of discrete hydraulically conductive structures) at a scale of metres to tens of metres prioritising the description of the connectivity of hydraulically conductive fractures.
- The creation of a DFN model of the studied rock block.
- The collection of information from hydraulic tests in core boreholes (in individual boreholes or between boreholes), subsequent testing using tracers and the mathematical simulation of the tests performed.

Research approach

- The gradual creation of a network of boreholes that intersect the selected rock block, which is located between corridors BZ-XIIJ, BZ1-XII and ZK-2.
- Mapping work in the underground spaces and the application of characterisation methods for the description of the boreholes (inclinometry, optical and acoustic television and other logging methods, water pressure tests, etc.).
- The equipping of the test boreholes with multi-packer systems for the conducting of hydraulic and tracer tests. Three boreholes will be equipped with multipackers with four sealing segments.
- The creation and refinement of a structural geological and hydrogeological model of the studied rock block and the simulation of the hydraulic tests.

Interim results

- The experimental site comprises a system of four boreholes equipped with multipackers. A total of 3 boreholes leading from the ZK-2 corridor (boreholes S-27, S-31 and S-36) with lengths of up to 70 metres each contain 4 packers and 4 monitoring stages. The 4th borehole (S-8) is located in the Vrk-1 corridor and, following the discovery that it communicated hydraulically with the other boreholes, it was equipped with a double packer and was included in the monitoring process.
- Following the installation of the multipackers in the boreholes, the monitoring of the establishment of pressure ratios was conducted for all the borehole monitoring intervals aimed at determining the natural pressure field in the rock block. This was followed by the conducting of simple connectivity tests via the systematic opening of selected intervals and the measurement of the pressure responses and outflows. The pressure field was homogeneous, as recorded for all the intervals both in-situ and in the models. However, once all the intervals had been opened, the heterogeneity of the fracture system was observed and the monitoring of the outflows from the various boreholes indicated increases of up to 4 times; in this case, the modelled outputs of the open intervals differed from the in-situ measurements.
- Short pulse tests and longer-term water pressure tests were subsequently conducted for selected stages of the boreholes aimed at the evaluation of the hydraulic conductivities of the tested sections of the boreholes (Fig. 21).
- A series of tracer tests are currently underway on selected pairs of borehole intervals with high connectivity.
- The modelling part of the project focused on the creation of a conceptual model of the rock block of interest (Fig. 22) including a stochastic fracture network in the outer regional model domain (from the ConnectFlow program), a detailed deterministic fracture network (from the MOVE program) and a supplementary stochastic network

(from the DFraM program) in the internal detailed domain. The model comprises a total of 43 continuous deterministic structures as evaluated from the boreholes and the corridor walls.

- A hydrogeological model (HydroDFN model) was created in two parallel branches to simulate the flow: 1. a regional HydroDFN model, 2. a detailed HydroDFN model of the rock block of interest. Other modelling activities are focusing on the simulation of the tracer tests.

Fig. 21 – Location of the Fracture Connectivity experiment in corridor ZK-2 during pulse testing (Zuna et al. 2022)

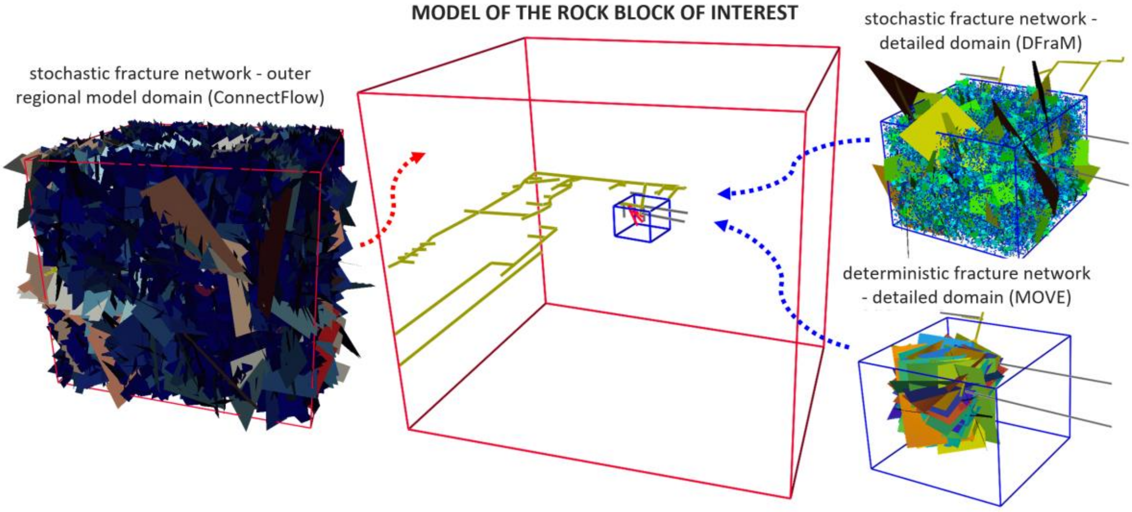

Fig. 22 – Diagram illustrating the composition of the model of the rock block (Zuna et al. 2022)

5.3 Characterisation II (2021–2025)

Project name: Geological and geotechnical characterisation of the rock environment – Bukov URF II

Participants: Czech Geological Survey; SG Geotechnika, a.s.; Institute of Geonics AS CR; INSET s.r.o.

Links to the DGR programme

The Bukov URF experimental programme is aimed at providing information for the refinement of the technical design concept of the DGR and at obtaining data for the creation of the models required to prove the safety of the concept. The Bukov URF research programme will allow for the in-time preparation of methodological procedures so that the work at the final DGR site can be carried out both efficiently and within the planned time horizon. The fulfilment of the Bukov URF experimental programme required the creation and equipping of new underground spaces. Therefore, in January 2021, excavation work commenced on the construction of Bukov URF II. The construction of the laboratory spaces and the associated characterisation comprises a research and development project in itself since it allows for the development and testing of mining methods and characterisation procedures for their future use in the construction of the DGR.

Objectives

- Determination of the geological and geotechnical parameters of the rock block on level 12 of the Rožná I mine, which will house the new complex of laboratory corridors. In a similar way to the construction of Bukov URF I (chapter 4.1), the project is intended to provide a comprehensive database of geoscientific data for its further use, i.e. to construct and verify the relevant descriptive and mathematical models.
- A comprehensive geological description of the rock block of interest with particular emphasis on the structural elements that are important in terms of the safety of the DGR and the selection of suitable sites for the planned experiments.
- The description and characterisation of the EDZ/EIZ in the vicinity of the newly-created corridors and chambers and the creation of a database for the further monitoring of the development of these zones.
- The creation of a classification system for future use in the construction of the DGR. The classification system will be used for the characterisation and definition of suitable rock blocks for the location of the DGR disposal areas.
- The drawing up of procedures, methodologies and recommendations for the characterisation and classification work required during the construction of the DGR.

Research approach

The research approach is divided into the following areas:

- Geological and structural-geological documentation.
- The petrographic and geochemical characterisation of the rock.
- A 3D structural-geological model; hydrogeological characterisation.
- The characterisation of the transport properties of the rock.
- The geomechanical and geotechnical in-situ and laboratory testing of the rock.

- Geophysical characterisation (Georadar, ERT - electrical resistivity tomography, shallow refraction seismic - surface refraction tomography; the seismic impacts of blasting work).
- The characterisation of the EDZ and EIZ.
- A rock block classification system.
- The 3D scanning of the excavated areas of Bukov URF II.

Interim results

- The research includes the mapping (structural and petrographic documentation) of the faces (Fig. 23) and walls of the excavated underground workings (Fig. 6).
- The characterisation research included the installation of two geotechnical stations (in corridors L4a and L7), which consist of a system of core boreholes designed for the conducting of geotechnical tests and the testing of geophysical methods. The boreholes were drilled using a DIAMEC Smart 4 drilling device with a DEVICORE BBT directional drilling tool, thus allowing for the drilling of oriented cores. The device enables the determination of the orientation of the core via the drawing of a line on the axis, from which the uncertainty of the core orientation can be derived. This line is also used to transfer the determined core values to the appropriate software for evaluation purposes.
- Drill columns that combine all the available data are being compiled for the documentation of the boreholes from the drill core scanner and the results of the ABI/OBI methods applied in the boreholes. Three relatively prominent fracture systems were identified based on the analysis of the walls of the three geotechnical boreholes drilled in corridor L7 performed using the OBI and ABI methods. The most prominent fracture system is spatially coincident with the metamorphic foliation with a general direction of dip to the SW and inclinations of 20° to 80°. Most of the open fractures are thus influenced by the metamorphic foliation. The second fracture system, with a general direction of dip to the WSW to NE mainly comprises open fractures with variable inclination from very flat structures with inclinations of around 5° to steeper fractures with inclinations of up to 80°. The third system consists mainly of closed fractures filled with mineralisation with a NNW or WNW direction and relatively steep inclinations of 70° to 85°. The high quality of the rock mass was evidenced by the minimal occurrence of zones of weakness.
- Corridors L5 to L8 feature gradual transitions along the foliation surfaces between paragneisses and amphibolites with varying degrees of migmatisation and frequent transitions to migmatite or migmatised amphibolite. Due to the character of the lithological environment, where biotite-rich lithologies often pass into amphibole-rich lithologies at a very small scale, the transition between the defined lithologies is difficult to map.
- The geophysical characterisation divided the rock mass along the line of the laboratory corridors into relatively only slightly disturbed sections and partially weakened sections. The detailed monitoring of the rock environment in the boreholes of the geotechnical stations and their surroundings was mainly conducted via the application of seismic tomography between the individual boreholes. The identified velocity sections provided the basis for the subsequent interpretation, which defined the occurrence of partially weakened rock. Induced rock weakening was also documented in the overburden of the laboratory corridors.

- The level of the groundwater in the URF II area is very low. The more pronounced inflows are linked to subvertical faults and fractures with a predominant dip direction of 250° to 310° and an inclination of 70° to 90°. The groundwater in the Bukov URF II environment is of the $Na\text{-}HCO_3$ to $Na\text{-}SO_4$ type; mixed types of water prevail ($Na\text{-}HCO_3\text{-}SO_4$, $Na\text{-}SO_4\text{-}HCO_3$). Sodium clearly predominates among the cations in all the samples taken. The total content of dissolved substances is in the range 200 to 370 mg/l.
- The application of stress measurement methods around the L7-87D borehole determined the following results: the maximum horizontal stress component *SH* = 42 MPa, the minimum horizontal stress component *Sh* = 19 MPa and the vertical stress component *Sv* = 14 MPa. The ratio of the values of the measured and received vertical and horizontal stress components of the rock mass *Sv : SH* : *Sh* were 1.0 : 3.0 : 1.4; the ratio of the horizontal stress components of the rock mass *SH: Sh* was determined at ~2.2:1. The azimuth of the main horizontal stress *SH* was 123°±15°. The orientation of the main horizontal stress components determined by means of the hydraulic fracturing of the borehole walls correlated well with the cross-sectional deformation analysis of geotechnical borehole L7-87D derived from measurements applying the ABI logging method.

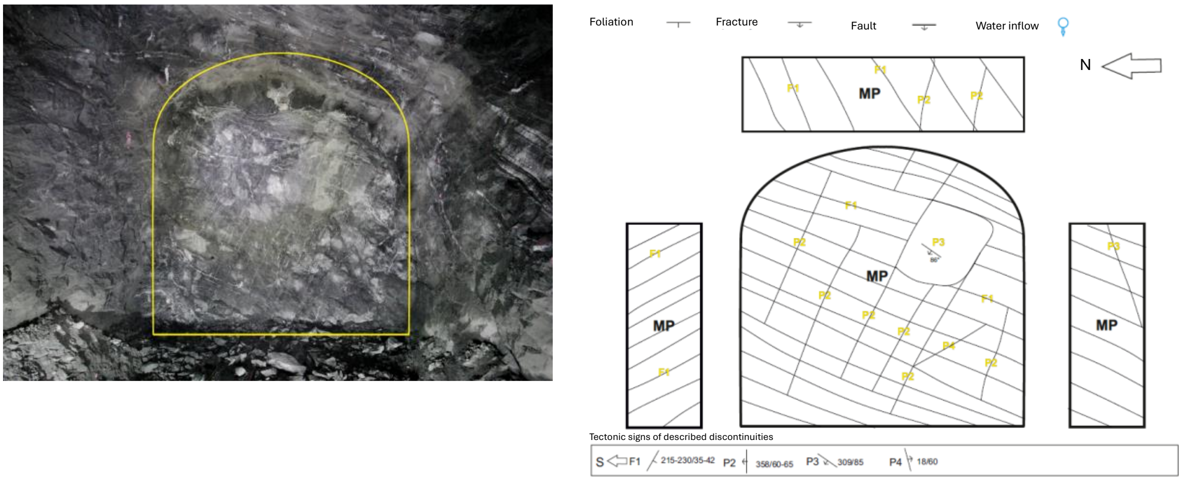

Fig. 23 – Example of the photo documentation and a drawing of the mine face in the geological documentation

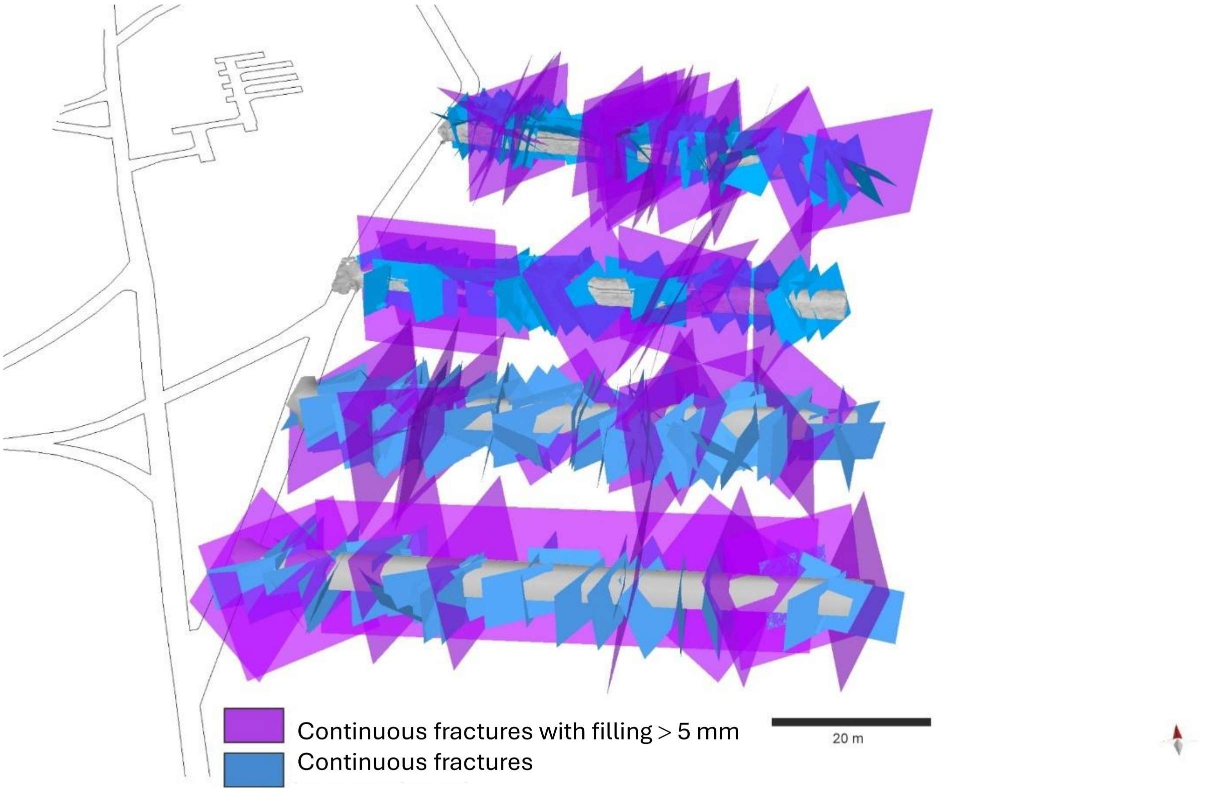

Fig. 23 – Image of the more significant fractures determined in the laboratory corridors

5.4 Corrosion experiment (2021–2034)

Project name: Pilot corrosion experiment in the Bukov URF

Participant: ÚJV Řež, a.s.

Links to the DGR programme

The waste disposal package (WDP) makes up one of the key engineered barriers in the Czech DGR concept. For the purposes of the granting of a licence for the proposed WDP design, it will be necessary to prove that the WDP meets all the relevant requirements (e.g. ensuring the removal of excess heat, preventing the occurrence of supercritical and subcritical conditions, a minimum lifespan as influenced by its mechanical stability and corrosion resistance). Thus, it is necessary to verify and demonstrate the behaviour of the materials used for the construction of the WDP under conditions that approximate to those expected in the DGR. The corrosion resistance and the corrosion rate of the WDP are two of the most important parameters in this respect.

Objectives

- The development of a methodology for the testing of the corrosion behaviour of metal samples and to obtain knowledge on the corrosion resistance of WDP candidate materials in the appropriate environment.
- The conducting of a pilot in-situ experiment so as to obtain data for the creation of mathematical models for the prediction of the corrosion resistance of the WDP candidate materials in the time horizon of the lifespan of the DGR.
- The evaluation of interactions between the WDP metal materials and bentonite.
- The evaluation of the influence on the properties of the groundwater of the presence of engineered barrier materials.
- The evaluation of the development of microbial activity in the rock environment and in the bentonite filling of the physical models focusing particularly on the contact between the metals and the bentonite. The description of the influence of microbial activity in the experiment due to increased temperatures.

Research approach

- The characterisation of a selected test chamber, the drilling of 10 experimental boreholes and their characterisation (geological documentation, chemical composition of the water, oxygen content, Eh, pH and microbiological settlement) followed by their monitoring. The drilling of a monitoring borehole (without corrosion modules). The detailed characterisation of the experimental materials under laboratory conditions.
- The determination of the methodological approach to, and the technical design of, the corrosion experiment. The preparation of physical models with corrosion modules (containing corrosion samples), their installation in the boreholes, the loading phase (heating so that the temperature on the surface of the corrosion samples reaches 70 to 95°C) and the removal of the models from the boreholes for the laboratory analysis of the materials (Fig. 24).
- Modules containing BCV bentonite with iron powder, carbon steel samples - base material and carbon steel samples – weld were installed in five boreholes. The other five boreholes were designated for modules with no added iron powder but with copper

or carbon steel - base material. Each of the modules contains a sufficient number of corrosion samples for the statistical evaluation of the corrosion rate. The modules contain heaters for the heating of the materials and the simulation of the DGR environment. The space inside the modules around the corrosion samples has been filled with compacted bentonite with a dry density of more than 1500 kg/m^3. The choice of the carbon steel samples was based on the Research and development of the disposal package for the deep repository project (Kotnour et al. 2019). The content of the modules will be analysed in the following time intervals: 1, 3, 5, 7 and 10 years.

- The experiment includes the hydrogeological and microbiological monitoring of the water. All ten boreholes can be fitted with additional corrosion modules following the removal of the original samples if deemed necessary during the course of the experiment.
- The inclusion in the experiment of an 11th module, which would not be equipped with a heating system, i.e. would contain comparable samples unaffected by heating, is currently under consideration.

Interim results

- The experiment is currently in the preparation of the corrosion module borehole installation phase. The results of the hydro-monitoring and microbiological monitoring provided information on the local conditions for the experiment in each of the boreholes.
- The Eh values were found to vary both over time and along the individual borehole profiles. Following drilling and during the first month of monitoring, the values were found to range between 222 mV (borehole K6) and 396 mV (borehole K2). The electrical conductivity (EC) in boreholes K1-10 was observed to vary between 480–660 µS/cm.
- The time development of the oxygen concentrations was monitored in selected boreholes. After around 5 days, the oxygen concentration dropped from 1.2 mg/l to the limit of detection (<0.02 mg/l) in borehole K3. A similar oxygen decrease trend was observed in borehole K5, in which the initial concentration was around 6 mg/l and gradually decreased to values of <0.02 mg/l within around 8 days. A different oxygen development trend was observed in borehole K6, i.e. only a slight decrease from 6.2 to 5.7 mg/l within around 14 days.
- The latest results of the microbial analysis indicated no increase in obligate anaerobes in the monitored boreholes, and no discernible trend was observed in terms of the development of the parameters in the individual boreholes over time. Microorganisms that use a combination of oxygen and nitrates currently dominate in the boreholes. The three sampling campaigns conducted to date indicate the absence of microbiological stabilisation linked to the establishment of reducing conditions in the boreholes. The results of the microbiological analysis thus correspond to the hydrochemical measurements. The measurement results suggest the presence of significantly different hydrochemical conditions in the individual boreholes (with concern primarily to the oxygen concentrations and oxidation-reduction potential).

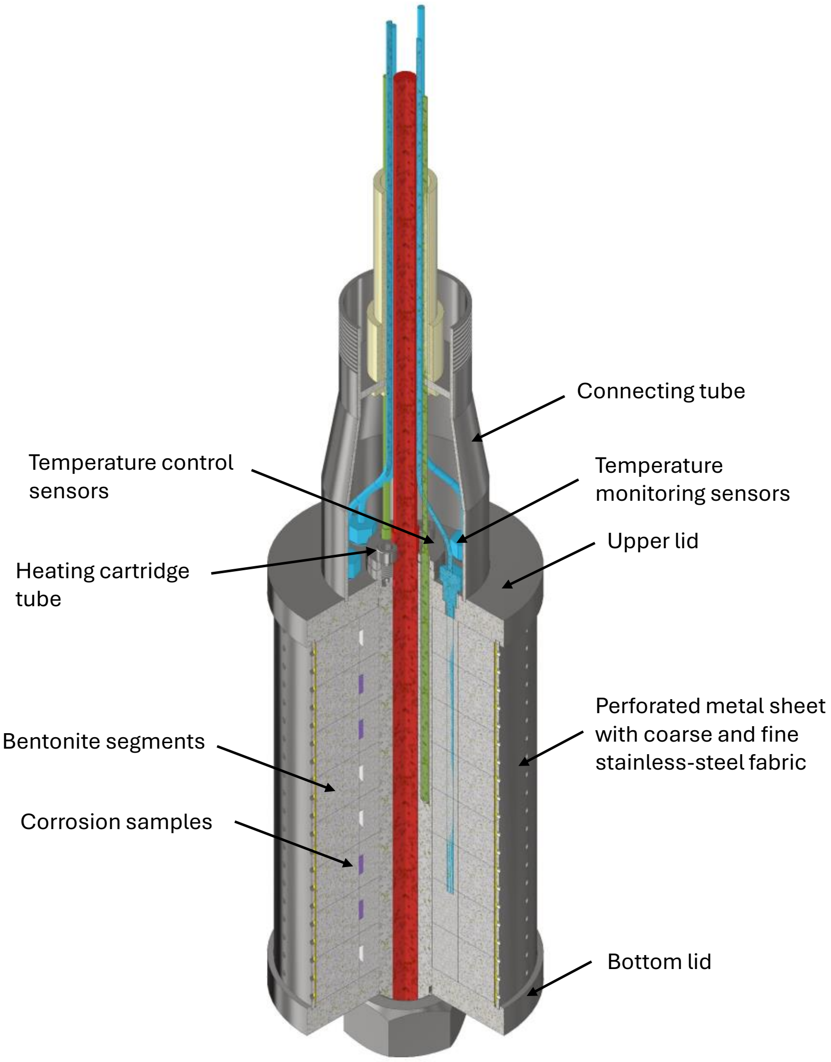

Fig. 24 – Image of a corrosion experiment module (Dobrev et al. 2022)

5.5 Temperature monitoring (2021-2025/2030)

Project name: Temperature monitoring of the rock mass in the Bukov URF and Rožná I mine

Participants: Technical University of Liberec, Faculty of Mechatronics, Informatics and Interdisciplinary Studies; Institute of Geophysics, AS CR

Links to the DGR programme

One of the basic prerequisites for proving the long-term safety and technical feasibility of the DGR comprises a detailed knowledge of the processes that take place at repository depth, concerning which, a knowledge of the temperatures of the rock mass at various depths below the surface and the temperature evolution of the rock mass in the vicinity of mine workings is essential in terms of the modelling of processes for the site safety assessment. This project is aimed at providing information on the temperature evolution of the rock mass near to open underground spaces, which forms a necessary prerequisite for the conducting of heat propagation-related experiments.

Objectives

- The acquisition of the real data needed for the creation of mathematical models for the simulation of heat propagation in the host rock of the DGR and the dimensioning of the underground corridors of the DGR.
- The determination of temperature values in the rock mass from the surface to a depth of 500 m (Bukov URF depth).
- The determination of the extent of the zone of thermal influence of the rock mass in relation to anthropogenic activity.
- The determination of the original temperature in the rock mass at measuring stations (prior to the excavation of the mine spaces) using a mathematical model and the prediction of the further development of related parameters based on a validated mathematical model.

Research approach

- The preparation of monitoring stations with boreholes equipped with temperature sensors. It is assumed that several stations will be created on the levels above the Bukov URF level near to the B-1 shaft, with a higher density of stations within the laboratory corridors on level 12, where it is possible to connect the instrumentation to the data network.
- The equipping of boreholes with temperature sensors to a depth of up to 15 m aimed at determining the temperature development curve with distance from the ventilated underground corridors. In addition to the monitoring of the temperature in the boreholes, the temperature and humidity of the air in the corridors in the vicinity of the monitoring stations will also be measured. The minimum temperature monitoring time will be 4 years.
- Mathematical modelling that prioritises the creation of a model of the temperature development in the rock mass at the locations of interest and the determination of the original temperature of the rock mass prior to the excavation of the underground spaces.
- The design of a follow-up calibration ventilation experiment that will provide data for the calibration of the mathematical model under precisely defined conditions. The experiment will contribute to reducing the inherent uncertainties and thus allow for the determination of more objective results from the heat propagation model of the rock mass. The technical design will be based on the isolation of part of a special test chamber, where it will be possible to regulate the air temperature using the ventilation system.

Interim results

- A network of the initial eight boreholes was commissioned in October 2022. Three 15-metre boreholes were drilled and equipped with instrumentation on the 3rd, 5th and 9th levels of the B-1 shaft. Two older boreholes and two new boreholes were instrumented for monitoring purposes in Bukov URF I and the final borehole is located near shaft B-2.
- Each of the boreholes has been equipped with ten temperature sensors. The temperature and humidity of the air are also measured at each of the locations.

- Geological models have been created for all the stations and the preparatory phase of the creation of mathematical models of the stations is underway.
- Laboratory investigation work is underway on rock samples from the boreholes aimed at determining the thermal properties of the rock matrix. The various parameters are determined using the optical scanning and the "Hot Disk" methods (Dědeček et al. 2022).
- The data collected over the first year indicates seasonal temperature fluctuations and the influence of the mine ventilation system (Fig. 26).
- Two more boreholes were instrumented in the Bukov URF II complex in October 2023.

Fig. 25 – End of a monitoring borehole and the measurement equipment

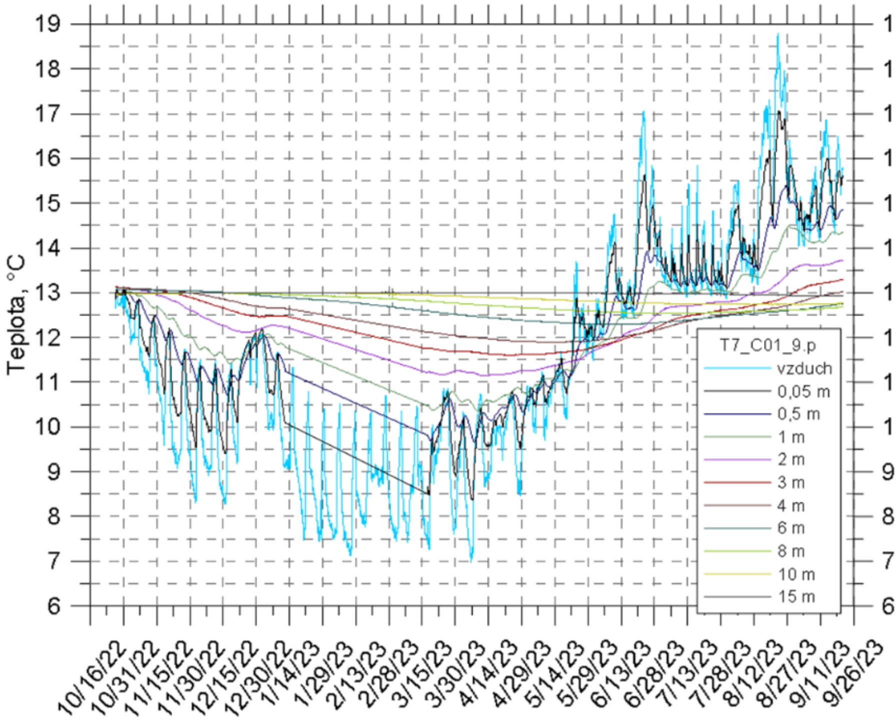

Fig. 26 – Development of the temperature in the borehole located on level 9 of gallery B-1

5.6 EURAD WP MAGIC (2021 – 2024)

Project name: EURAD - Chemo-Mechanical ageing of cementitious materials under coupled disturbances based on a multiscale approach

Participants: Czech team – SÚRAO, CTU in Prague, ÚJV Řež, Technical University of Liberec, CVŘ

Links to the DGR programme

It is planned that concrete with a reduced pH will be used as one of the structural materials in the DGR (e.g. for the stabilisation of the corridors and the construction of sealing plugs). The main advantage of reduced pH concrete lies in the fact that it will not negatively affect the behaviour of bentonite, which will have a fundamental safety function in the DGR. In 2019, SÚRAO commissioned the development of concrete with reduced pH (Pernicová et al. 2019), which included the casting of test samples for the verification of the stability of the material over time. The MAGIC experiment simulates the interactions between materials under conditions that correspond to the first few years following the construction of concrete structures in the DGR disposal horizon.

Objectives

- The study of the mechanical, chemical and structural properties of concrete with reduced pH under various conditions relevant to the future DGR, including the consideration of the influence of microorganisms.
- The verification of the properties and stability of the newly-developed concrete with respect specifically to its reduced pH using test samples (see Pernicová et al. 2019).

Research approach

- The laboratory testing of samples at the beginning of the MAGIC project (3 years after the casting of the samples) and after 2 years of the duration of the project (5 years after the casting of the samples). The samples (exposed to air) are stored in Bukov URF I at the end of corridor BZ1-XII (Fig. 27).
- The preparation of samples for environmental impact testing (cylinders, discs, ground material).
- The ageing of the samples in three different environments - groundwater, a bentonite suspension and natural air humidity in the underground facility. These samples are located in the transport corridor that connects Bukov URF I and Bukov URF II (Fig. 28). Aimed at the testing of the impact of the presence of groundwater, flow boxes have been installed that are connected to a source of groundwater from the S-25 borehole. Installation took place in March 2022.
- The laboratory testing of the ageing samples after 6, 12, 18 and 24 months.

Interim results

- The initial results from the testing of the samples indicated increasing compressive strength over time and a slightly decreasing pH trend.
- The interim results have been presented in the context of the EURAD project. A report that provides a summary of the final results will be prepared at the end of the project

Fig. 27 – The storage of samples in air

Fig. 28 – The MAGIC project site with the flow-through boxes

5.7 Stress (2023-2025/2027)

Project name: Determination of in-situ stress in the Bukov URF II

Participant: Institute of Geonics AS CR

Links to the DGR programme

The planning of the DGR requires, *inter alia*, the verification of the dimensions and orientations of the main geostatic stress directions in the selected rock mass. Thus, it is necessary to design and test a method for the monitoring of stress that can be applied during both the construction and operational phases of the DGR. The Bukov URF provides an ideal opportunity for the testing of methods that are still in the development phase at a depth corresponding to that of the future DGR with similar geostatic stress parameters.

Several different methods have been applied in the past at the Bukov URF so as to obtain data for the determination of the stress tensor. Methods for the determination of the stress and the long-term monitoring of stress changes in the vicinity of underground corridors were applied at several locations as part of the Characterisation I (chapter 4.1), EDZ (chapter 4.2) and Deep horizons (chapter 4.4) projects. Measurements were taken using strain gauge bolts, a method involving the relieving of the weight of borehole cores, the hydraulic fracturing of borehole walls method, and long-term stress monitoring using cone strain gauge probes in boreholes. Additional information was also provided via inverse modelling using data from convergence measurements. All the methods applied to date at the Bukov URF yielded relatively different direction and stress component magnitude values. These differences were due partly to the heterogeneity of the local rock mass and partly to the uncertainties and inaccuracies inherent in the methods applied. This project is intended to provide new information from the Bukov URF II complex aimed at refining the approach to the measurement of stress.

Objectives

- The design and implementation of a procedure for obtaining data on, and evaluating the stress of, the Bukov URF II rock mass via the application of methods used in the past in Bukov URF I and other parts of the mine (convergence measurements and the related inversion analysis, methods for measuring deformations in boreholes with cone strain gauge probes, the hydraulic fracturing of borehole walls).
- The summarisation of all the available data (from this and other related projects) and the evaluation of the stress tensor in the Bukov URF II area.
- The design and implementation of an experimental method for determining stress via the measurement of deformations using large-profile core boreholes.
- The processing of research methods and the study of the use of stress measurement methods in the DGR construction and operation phases.
- The suggestion of a follow-up research programme and in-situ experiments related to in-situ stress.

Research approach

- The monitoring and analysis of the development of stress in a stress pillar (the rock block between corridors L4a, L4b, L4c and L4d) and its surroundings applying the convergence measurement method and cone strain gauge probes (CCBO and CCBM methods).
- The testing of a new method for the measurement of the deformation of core boreholes with a diameter of 300 mm drilled into the walls of corridors near to the face of excavated mine working.
- The provision of support for mathematical modelling.

Interim results

- Two core boreholes were drilled from the area of the L4a corridor prior to the commencement of the excavation of the L4b corridor in Bukov URF II. The Compact Conical ended Borehole Overcoring (CCBO) method was applied in the boreholes and probes were installed at the ends of the boreholes for long-term monitoring purposes (CCBM). The two probes, positioned in the centre of the stress pillar, will allow for the monitoring of changes in the stress due to the excavation of the surrounding corridors.
- The first convergence stations were installed during the excavation of the L4b corridor. Corridor convergence is being measured using a common convergence band and via the repetition of the laser scanning of the corridors at the station locations (Fig. 29).
- The first 2 experimental core boreholes with a diameter of 300 mm designed for the measurement of deformation have been drilled in the L4b corridor.

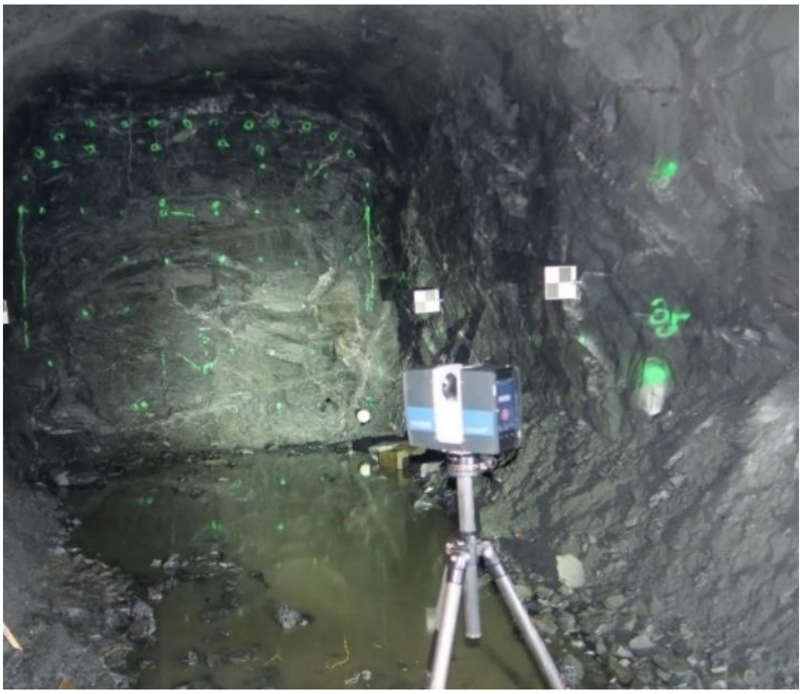

Fig. 29 – View of the location of the convergence station in corridor L4b with a laser scan device

5.8 Contour blasting (2023)

Project name: Contour blasting work during the excavation of test chambers in the Bukov URF

Participant: Montanika z.s.

Links to the DGR programme

When using blasting for the excavation of the mine workings of the DGR, proven procedures will be applied that exert the minimum possible impact on the disturbance of the surrounding rock mass (the extent and parameters of the EDZ and EIZ). The excavation of Bukov URF II provides a unique opportunity to test and compare various contour blasting methods.

Objectives

- The excavation of the rock mass applying various blasting technology modifications with regard to the influence on the rock mass in the vicinity of the excavation work.
- The evaluation and comparison of corridors excavated using different procedures.

Research approach

- The application of various approaches to the blasting of five test chambers excavated from the L7 corridor (ZK7-1S, ZK7-1J, ZK7-2J, ZK7-2S, ZK7-3J). The modifications comprise, for example, adjustments to the arrangement of the boreholes (drilling schemes), the use of different types of charges and the adjusting of the order and timing of the blasting of the boreholes (Fig. 30).
- Excavation work.
- The evaluation of the quality of the excavation work and the state of the rock mass around the corridors. The use of geophysical methods is assumed with concern to the

evaluation of the parameters and the extent of the EDZ. The comparison of the modified procedures with the normal procedure employed for the excavation of laboratory corridors.

Interim results

- All the test chambers in corridor L7 were excavated between March and June 2023.
- Characterisation and evaluation work is currently underway.

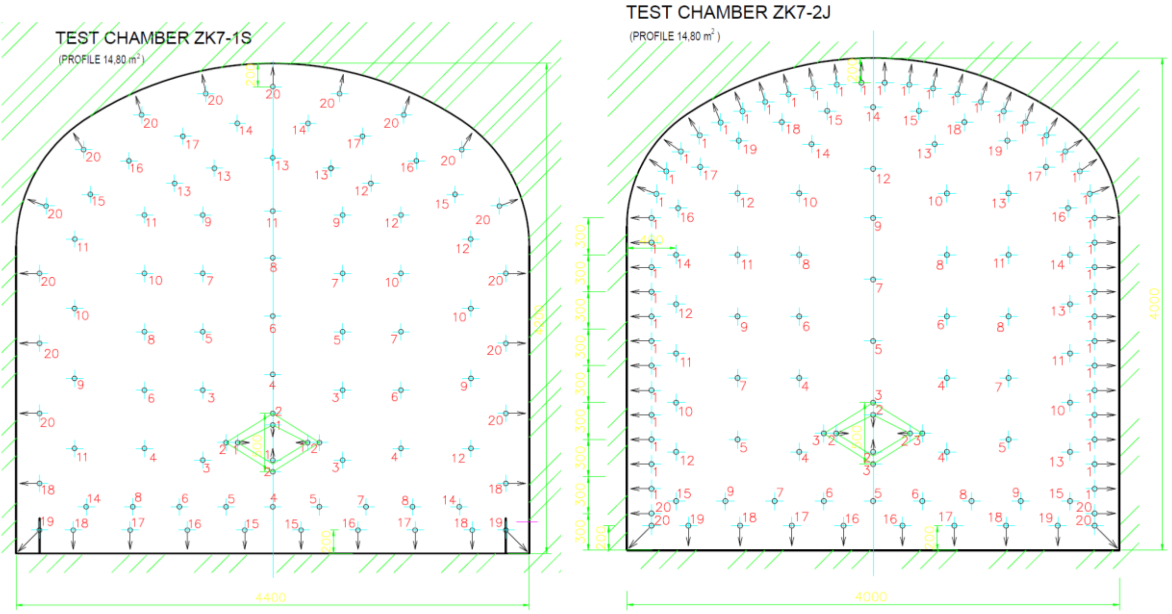

Fig. 30 – Comparison of the two selected drilling schemes

6 The areas covered by the R&D plan and their current status

This chapter provides a description of topics that are currently being researched and which have already been partially concluded (in connection with the projects described in the previous chapter) or for which new projects are assumed (new or supplementary experiments). Compared to the first version of the Bukov R&D Plan of 2021 (Smutek et al. 2021), the structuring of the various research areas has been adjusted and a section has been added that contains a description of their current status. Tab. 5 provides an overview of the considered research fields with references to the main areas of the SÚRAO research programme (see chapter 2.4).

Table 5 – Overview of the areas addressed in the R&D plan

Area	Main area of the SÚRAO research programme
Chapter 6.1.1 Rock classification systems	REP1
Chapter 6.1.2 EDZ and EIZ characterisation	REP5
Chapter 6.2.1 Advection-dispersion transport processes	REP3
Chapter 6.2.2 Diffusion processes	REP3
Chapter 6.2.3 Modelling concepts in the area of groundwater flow	REP3
Chapter 6.2.4 Uncertainties concerning in-situ transport parameters	REP3
Chapter 6.2.5 Flow in EDZ and EIZ	REP5
Chapter 6.3 Testing the construction and characterisation of disposal wells	REP6
Chapter 6.4.1 Low pH concrete	REP4
Chapter 6.4.2 Long-term laboratory	REP4
Chapter 6.4.3 Experimental study of THM(C) processes – HEAT experiment	REP4
Chapter 6.4.4 Bentonite erosion and colloid transport (ERO)	REP4
Chapter 6.4.5 Buffer expansion into the backfill and WDP loading (EXP)	REP4
Chapter 6.4.6 Demonstration experiment of a prototype repository (DEMO)	REP7

6.1 Characterisation of the rock environment

Based on changes to the Czech DGR development programme in recent years related primarily to the shortening of the DGR preparation time-line, research activities connected to the drilling of a deep test borehole from the surface (area: the description of the isolation area of the repository via drilling) are no longer included in the Bukov URF research programme. Due to the bringing forward of the date for the commencement of drilling investigation work at the DGR candidate sites, it was decided that this activity was unnecessary and it was subsequently removed from the plan. The rock classification systems and EDZ and EIZ characterisation research areas mentioned below have already been partially addressed in the context of the ongoing projects described in chapter 5.

6.1.1 Rock classification systems

Links to the DGR programme

Rock environment classification systems serve to define the basic requirements for the layout of the DGR and the basic parameters of the DGR isolation area (Andersson et al. 2000; Hagros et al. 2005). It is important to use data obtained from a depth that corresponds to that of the future DGR to accurately define such systems. This area is related to chapter 9.2.2 of the SÚRAO 2020 R&D Plan.

Objectives

- The determination of a rock classification system for the purpose of accurately describing the DGR environment and for defining the suitability of the rock environment, including geomechanical, hydrogeological and hydrogeochemical considerations in addition to the geological characteristics.
- The testing of the classification system, modified according to the specifics of the rock environment of the Bohemian Massif, in the Bukov URF.

Research approach

Established classification systems (e.g. Barton 1987; Bieniawski 1989; Andersson et al. 2000; Hagros et al. 2005) will be re-evaluated aimed at creating a specific SÚRAO classification system. The environmental parameters that impact long-term safety will be assessed (near and far-field interactions) and the complexity of the design and construction of the DGR (excavation, drilling, mechanical rock stability, groundwater inflows, etc.) will be assessed with regard to the DGR requirements management system, while fully respecting the long-term safety objectives of the repository.

The key parameters that will be employed to create the classification system include the lithology of the host rock (mineral composition, foliation, grain size, porosity, etc.), regional and local fault zones, brittle deformations, the mechanical properties of the rock and disturbances (strength and deformation), the stress state, the thermal properties of the rock, the temperature of the environment, hydrogeological parameters (hydraulic parameters, water viscosity, etc.), the hydrogeochemistry and transport properties.

Current status

In connection with the ongoing Characterisation II project (chapter 5.3), the research team is testing the so-called Rock Block Classification system. The project is making use of the gradual acquisition of data during the excavation of the Bukov URF II complex. The initial version of the classification system was based on a Finnish concept. The tested classification system comprises two stages. The aim of the first stage is to assess whether or not it is appropriate to excavate an access (loading) corridor to the disposal wells based on information provided from the research of pilot boreholes. The parameters assessed in the first stage consist of: the RQD classification index, the seismic wave propagation velocity and the hydraulic conductivity of the rock. The second assessment stage considers the following determining parameters: the number of Q classification index points (Barton 1974) and the seismic wave propagation velocity with the aim of defining suitable locations for the disposal wells. Suitable sections are reduced in extent in both the assessment stages via the consideration of “critical volumes” around “critical structures” (terms included in the Finnish classification system: Hagros et al. 2005), or via the geochemical limits of the environment.

6.1.2 EDZ and EIZ characterisation

Links to the DGR programme

Parts of the rock mass in close proximity to excavated mine workings are necessarily damaged or disturbed by the excavation process, concerning which it will be necessary to apply tried and tested methods so as to verify the extent and characteristics of the damaged (EDZ) and disturbed/influenced (EdZ, EIZ) areas of the rocks in the vicinity of the underground workings in the future DGR. Such methods are currently in the development phase. The EDZ is particularly important since it potentially has one to three orders of magnitude higher permeability than the undamaged rock mass and, thus, may provide preferential pathways for the transport of water and/or other substances.

This issue is being researched on a continuous basis in the Bukov URF and important data has already been obtained primarily from the EDZ project (chapter 4.2) and geophysical method-related projects (chapters 4.6 and 4.11.1). The main shortcoming of the research conducted to date concerns the impossibility of interpreting the results of the geophysical measurements in terms of the more precise determination of the extent of the damaged area. In this respect, it will be necessary to supplement these measurements with direct observation methods. Valuable additional information will be provided by the Characterisation II project (chapter 5.3), which includes the conducting of hydrotests in short boreholes aimed at monitoring changes in the permeability of the EDZ.

Objectives

- To supplement existing knowledge of the properties and extent of the EDZ and EdZ/EIZ of the Bukov URF rock mass applying methods that have not been considered in previous projects or in the ongoing Characterisation II project (chapter 5.3).
- The evaluation and proposal of methods for characterising EDZ and EdZ/EIZ during the various phases of the construction and operation of the DGR.

Research approach

The project involves the consideration of specialised methods to obtain direct measurement data for the interpretation of the extent and properties of the EDZ and EdZ/EIZ. A special test chamber will be prepared for the taking of long-term measurements in the context of the monitoring of the EDZ and EdZ/EIZ. Particular attention will be devoted to the EDZ, the extent of which in crystalline rocks ranges from decimetres to the first few metres.

The methods being considered for inclusion in the project include, for example, fracture system mapping applying the injection of resin into the rock in the EDZ area, sample drilling (for example, using a wire saw) and the laboratory analysis of the injected pore space. The research will also include the evaluation and design of methods for use in the DGR, where, especially during the construction phase, it will be necessary to take measurements that can be applied to the entire spatial extent of the underground complex within a strictly limited time period.

Current status

Equipment designed for the conducting of water pressure tests in very short sections of core boreholes has been designed and tested as part of the ongoing Characterisation II project (chapter 5.3). A series of short subvertical core boreholes with lengths of 1 or 2 m is being drilled in the Bukov URF II complex for the conducting of systematic water pressure tests aimed at determining the hydraulic conductivity of the respective sections. The double packer injection equipment allows for the testing of hydraulic conductivity at various depth levels in the boreholes, including sections in the vicinity of the EDZ. The interpretation phase will include the comparison of the hydraulic conductivity results with the results of the geophysical measurements taken on the walls of the corridors into which the test boreholes have been drilled.

6.2 Migration of substances in the rock environment

These experiments are intended to fulfil objective no. 4 of the SÚRAO 2020 R&D Plan, namely the Verification of the Prediction of the Transport of Mobile Radionuclides in the Isolation Part of the Repository. The experimental programme includes the continuation of the study of substance transport processes in the fractured environment of crystalline rocks applying both active and inactive tracers and a related mathematical modelling programme.

The basic transport processes in the rock environment comprise advection, hydrodynamic dispersion, sorption/retardation and diffusion into the rock matrix (Fig. 31 and Fig. 32). Advection is given by the velocity of the movement of water in the rock environment, the value of which is the ratio of the specific flow rate and the effective porosity. Hydrodynamic dispersion is caused by molecular diffusion in water and mechanical dispersion, which is the result of the unevenness of the flow in the longitudinal, transverse and vertical directions. Diffusion into the matrix occurs from fractures into saturated rock with non-flowing water. In addition to the diffusion coefficient in water, rock parameters such as tortuosity and porosity also enter into the description of diffusion into the rock matrix. The final main process comprises sorption on the surfaces of fractures and fracture fillings. In the case of sorbing radionuclides, sorption is likely to comprise the main retention mechanism. Transport mechanisms depend on the properties of the mobile phases, which may change in terms of time and space (chemistry, temperature, density, dynamic viscosity). Other processes include colloid transport, which may represent the main mechanism of long-distance migration, especially with respect to strongly sorbing radionuclides. Depending on the mobility of the colloids, this mechanism will comprise either a retarding or, in the case of mobile colloids, an accelerating transport function.

In addition to the distribution of fractures, which is traditionally represented by a network of polygons, the above-mentioned processes are strongly influenced by the inhomogeneities within individual fractures (i.e. channelling; Fig. 32). The internal inhomogeneities of fractures impact the retention times of radionuclides via the variability of the volumes of flows inside the fractures, which act to shorten or lengthen the retention time depending on the interconnectedness of the internal structures. In contrast to homogeneous fractures, it also leads to changes in the contact areas of migrating radionuclides, which is reflected in the ratio of absorbed radionuclides to the surface of the fracture or the fracture filling, and may also act to change the values of diffusion into the matrix (the ratio of the amount of diffused radionuclides to the total amount).

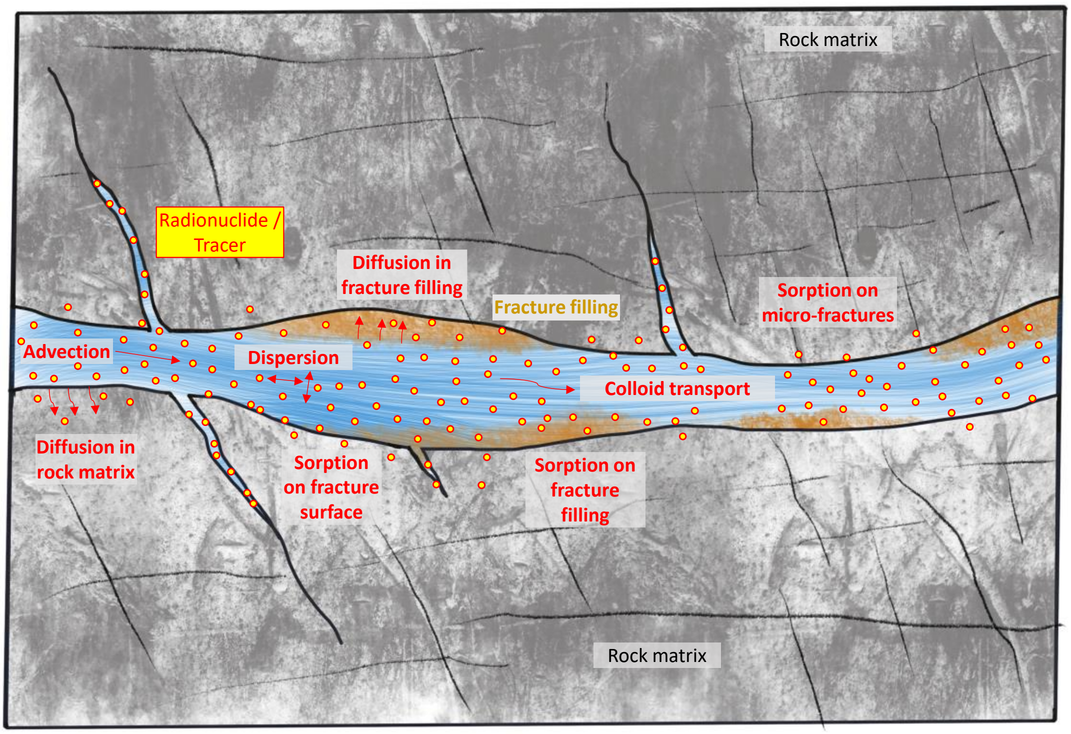

Fig. 31 – Scheme of the transport processes at work in a fractured environment in 2D

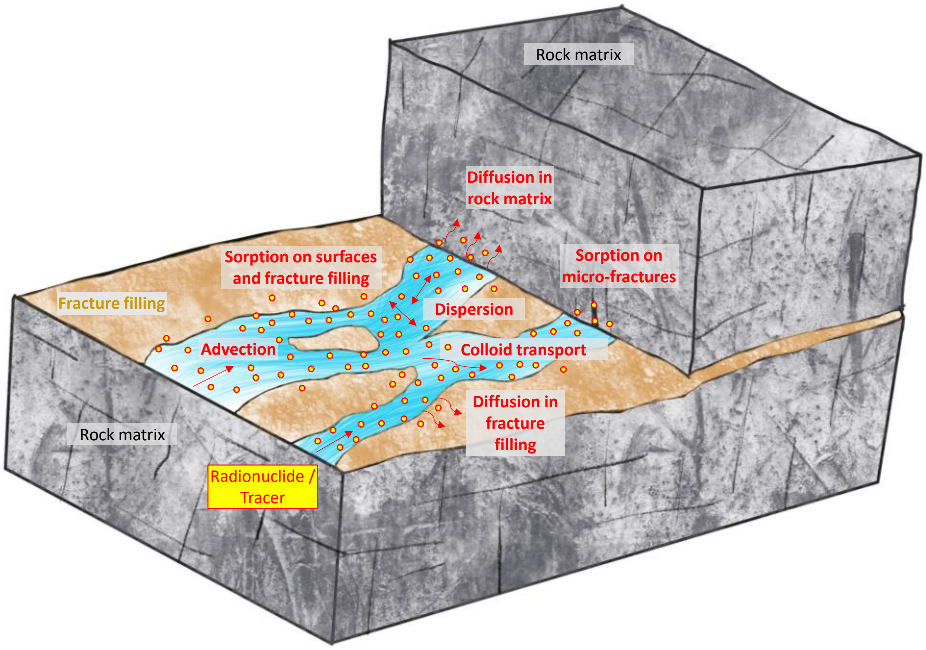

Fig. 32 – Scheme of the transport processes at work in a fractured environment in 3D

The migration of substances research programme commenced with the conducting of the Fracture Connectivity project (chapter 5.2), the interim results of which indicate the significant tectonic failure of the selected rock block with the presence of fracture zones with thicknesses in the order of decimetres. Moreover, very low pore water pressure values were determined in the water-bearing structures, which indicated the interconnectedness of the fracture systems with the complex of corridors. Although the location chosen for the conducting of this project is suitable for fulfilling the basic objective of the project, i.e. the study of the interconnectedness of fracture systems, the investigated rock block will probably not sufficiently represent the disposal spaces in the DGR (the isolation part), thus the selection of a new location for the conducting of migration tests in the Bukov URF II complex is planned.

Two methods are considered with respect to the study of diffusive transport, one of which concerns the conducting of a stand-alone long-term diffusion experiment in separate boreholes (minimum of 3) as described in the 2019 plan of experiments (Svoboda et al. 2019). This approach is based on experience gained from the LTD project conducted at the Grimsel Test Site (Havlová et al. 2018) and the LTDE project at the Äspö HRL (Löfgren and Nilsson 2020) and the related Task Force 9 programme (Soler et al. 2017; Hokr et al. 2020).

The second approach considers a combined experiment that monitors advection, diffusion and sorption processes (and, potentially, dispersion, which does not have to be considered in the case of directed flows through fractures). This method would involve finding a suitable discrete fracture (at a newly-determined inter-borehole tracer test site) which, following detailed characterisation research, could be used for tests employing radionuclide cocktails (or other tracers that represent different sorbing radionuclides) in a similar way as that planned in the LTD project (Phase 4) at the Grimsel Test Site. In this case, a radionuclide tracer test is being prepared in a selected shear zone with mineral infill for a distance of approx. 1.2 m. The LTD project is currently progressing from the study of simple diffusion into a granite rock matrix to a more complicated system of a fracture filled with minerals and altered rock where diffusion contributes to the retention of radionuclides during advective transport through the fracture. The project considers processes surrounding diffusion and sorption with respect to the mineral infill and the rock matrix, as well as advection processes. The LTD experiment is thus attempting to approximate the real behaviour of radionuclide migration in a well-characterised fracture.

Ideal conditions for a combined type experiment:

- A discrete, well-defined fracture in the saturated zone of a monotonous part of the rock mass with mineral infilling and slow groundwater flow.
- The availability of a tested fracture with the potential for drilling and extracting a rock sample.
- The potential for conducting a sufficiently long tracer test with radionuclides.

The research programme assumes the conducting of tracer tests first with inactive and then with active tracers. The advantage of using active isotopes under in-situ conditions concerns the ease of detectability when using low radionuclide concentrations or low-activity radionuclides. The disadvantage concerns the relatively strict legislative conditions.

From the point of view of modelling, this experimental area will provide data for the simulation of the transport of radionuclides following their escape from damaged WDPs. Radionuclides may be transported in the form of solutions with water through the engineered barriers and the geosphere and eventually into the biosphere. The main processes that influence the migration and retention of radionuclides comprise advection, sorption and diffusion in addition to gases and colloids. The results of the planned in-situ experiments will be used to create models of the geosphere part of the transport pathway, in which the properties of the flow pathways (fractures) and the retention properties of the rock matrix will be entered as input parameters.

The two areas of interest of the research programme are described separately below due to their potentially being implemented separately (chapters 6.2.1 and 6.2.2).

6.2.1 Advection-dispersion transport processes

Links to the DGR programme

See the introductory part to this chapter.

Objectives

- To improve the overall understanding of processes surrounding the transport and retention of selected tracers in the fractured environment of the Bukov URF and the testing of models that can be used to describe these processes.
- The credible simulation of flow in the isolation part of the deep geological repository applying the appropriate mathematical approaches.
- The conducting of tracer experiments using inactive tracers and dyes and, possibly, radioactive tracers, the significant advantage of which is their ease of detection in very low concentrations and the more realistic simulation of the transport processes of the radionuclides released from the WDP.

Research approach

The project will include the selection of a site and the preparation of the site for the conducting of such types of tests, the initiation of the construction of the required laboratory and the conducting of related mapping and characterisation research. The target parameters of the rock block for the performance of the tests comprise low permeability and the absence of significant hydraulically conductive zones that must not traverse the disposal wells in the DGR. The rock block should also be as unaffected as possible by the surrounding open corridor spaces. The rock mass should be saturated with groundwater, the pore water pressure should be as high as possible, and the water-bearing fracture systems should not communicate to any significant extent with the laboratory corridors.

A network of core boreholes will be drilled in the selected rock block to allow for the conducting of the initial characterisation research. In the first phase, the boreholes will be used for the long-term monitoring of the hydraulic conditions in the rock block and for the conducting of basic hydraulic tests. It will also be possible to supplement the hydrotests with gas permeability tests. A geological and hydraulic model of the rock block will be created, which will be used to simulate subsequent tests. The detailed mapping and interpretation of the hydraulic behaviour of the rock block, supported by a validated hydraulic model, will be necessary prior to the conducting of the tracer tests.

The test boreholes will be fitted with multipackers that will serve to isolate the selected structures of interest. Concerning the study of transport processes, the presence of a separate hydraulically conductive fracture intersected by several boreholes, an already mapped and characterised network of fractures, and anaerobic conditions will be advantageous. The tracer tests proper will commence following the conducting of basic hydrotests between the multipackers that will serve to define the hydraulic connectivity and hydraulic parameters of the rock. A typical tracer test involves the injecting of the selected tracer or a mixture of tracers into the chosen borehole stage, the monitoring of the concentration of the tracer in the borehole and the monitoring of the breaktrough curves. In general, such projects involve the monitoring of the flow velocity, diffusion into the matrix, dispersion and, possibly, the wetted surface of the fracture. The in-situ research will be supplemented by a detailed laboratory programme and will be linked to modelling activities.

Tests with active tracers can only be performed in so-called controlled zones for working with sources of ionising radiation in accordance with the requirements of the Atomic Act and Decree 422/2016 Coll. Therefore, prior to the start of the research, it will be necessary to obtain permission from the SÚJB for the conducting of certain types of experiments

Current status

The excavation of a new section of the Bukov URF II laboratory is currently underway. The characterisation and monitoring research performed during the excavation work demonstrated the presence of very compact rock with a number of areas without any significantly hydraulically conductive fracture zones. The water pressure tests carried out in selected boreholes indicated the presence of very long sections with extremely low hydraulic conductivity. The monitoring of the hydrostatic water pressures in the pilot boreholes of the excavated corridors demonstrated that the rock mass is saturated with groundwater and that the water pressure values are up to 1.2 MPa. These characteristics concern mainly the southern part of the complex in the surroundings of corridors L7 and L8, which features very high quality rock. The test chambers in corridor L8 have been assessed as a suitable location for future planned activities in this research area. Potential follow-up activities will also depend on the results of, and the recommendations provided by, the Fracture Connectivity project (chapter 5.2).

6.2.2 Diffusion processes

Links to the DGR programme

See the introductory part to this chapter.

Objectives

- To improve the overall understanding of diffusion processes in terms of migration into the rock matrix and fractured environments (estimation of the retention functions of the rock mass).
- The acquisition of data for the creation of mathematical models that describe the process of diffusion into the rock matrix and fractured and faulted environments.
- The comparison of the results of the in-situ experiments with those provided by the laboratory research of rock samples (upscaling) and the comparison of the results obtained from the Bukov URF tests with those from similar tests conducted at the Grimsel Test Site and the Äspö HRL.

Research approach

One of the potential experiments involves injecting a solution of tracers from an injection borehole into the rock mass, in which the solution is left for a defined period of time, during which changes in the tracer concentration/activity are monitored in the surrounding monitoring boreholes along with the development of the diffusion process. Such types of experiment require an intact block of rock without the presence of tectonic structures and with advective water flow in the fractures. Furthermore, the full saturation of the rock block and anaerobic conditions (which are important for redox-sensitive radionuclides) are required. It is recommended that the experiment be conducted employing a system of three boreholes: one borehole serves for the injection of the tracer and the other two for monitoring purposes. The interval selected for the injection of the tracer in the injection borehole is isolated using a multipacker device. This is followed by the preparation of a circulation system for the injection of the tracer solution and the sampling of the water. The monitoring boreholes are also fitted with multipackers and serve for the monitoring of the arrival of the tracer solution. Following the injection of the tracer, samples are taken and the hydrochemical parameters of the water are measured in all the sections isolated by the multipackers. In the case of the use of radioactive tracers, it is advisable to incorporate a system for the online detection of the activity in the boreholes.

The tracers will be selected with regard to the required outputs of the experiment. In general, combinations of a conservative non-sorbing tracer, anions and weakly and strongly sorbing cations are applied. The concentrations (activities) of the tracers are selected taking into account the local properties of the rock, the sensitivity of the analytical methods and the legislative conditions governing the conducting of such types of tests as valid for the given location. The duration of the tracer test is expected to be in the range of months to the first few years. The experiment will be concluded by removing the multipacker from the injection borehole and ensuring that the tracer solution remains within the rock via the injection of resin. The borehole is subsequently overcored applying a larger diameter and the resulting cores are then subjected to laboratory analysis. The diffusion profile is determined for sorbing tracers.

All the in-situ research will be accompanied by a laboratory testing programme and modelling. In the case of the application of radioactive tracers, permission must first be obtained for the conducting of the tests. The safety of the personnel directly involved in the experiment, other persons in the underground complex and the environment must be ensured at all times.

Current status

The decision to include this particular experiment and to refine the respective technical specification will be influenced by the progress of other related ongoing research.

6.2.3 Modelling concepts in the area of groundwater flow

Links to the DGR programme

Data from the DGR depth horizon will be obtained from deep boreholes as part of the characterisation research of the candidate sites for the DGR and the creation of 3D descriptive models of the sites. Therefore, it is necessary to determine and test procedures in advance for the extrapolation of point and borehole data to 3D models. A number of previous SÚRAO projects that addressed the description of fracture environments (Gvoždík et al. 2020; Kabele et al. 2017; Zuna et al. 2022) contributed to the determination of a procedure for the creation and transfer of field data to DFN models. Most of the models were refined using data on surface outcrops and underground tunnels, which provided information on the frequency, orientation and probable extent of the fracture systems. The DGR site survey work will serve to expand the fracture dataset for the creation of DFN models and will provide further information on fractures from DGR depth from boreholes, which, however, will not include data on the lengths of the fractures. Hence, it will not be possible to optimise the power distribution parameters of the fracture sizes at the DGR depth horizon as in the models based on data obtained from the corridors of the Bukov URF, and it will probably be necessary to estimate these parameters. Therefore, the need remains to test modelling procedures for the creation of DFN models based on a combination of surface and borehole data.

Objectives

- The validation of fracture network and flow geometry models in a fractured environment that can be used to describe flows at the candidate DGR sites.

Research approach

The first phase will comprise the creation of a predictive model. The fracture network will be modelled in the form of a “blind prediction” using borehole-derived data (the distribution of fractures along boreholes and their orientations and apertures etc.) that imitates the situation at the DGR sites during the site investigation stage so as to allow for the description of the sites. The hydraulic parameters (transmissivity) of the fractures will most likely be interpreted on the basis of known correlation relationships, especially the fracture size and transmissivity correlation. The application of the geomechanical approach (i.e. using in-situ measured data, for example stress) to the modelling of fractures will allow for the supplementing of the original statistical data obtained from boreholes with data obtained from the monitoring of stress. Should any outcrops be discovered in the vicinity of the Bukov URF, the information they provide on the fractures system will be included in the model.

The validation of the models will take into account data obtained from both the mapping of the walls of the corridors and the monitoring of stress, which can be used, for example, in the interpretation of the permeability depending on the stress directions, or even directly for the refinement of the fracture network parameters. Furthermore, a DFN model will be created for comparative purposes using all the data acquired, including newly obtained data from the mapping research. As with the predictive model, the hydraulic parameters of the fractures will also be interpreted and a hydraulic simulation performed, the results of which (mainly flow rates) will serve for calibration purposes in the subsequent experimentation stage. Following the selection of the most appropriate method, the model will be calibrated and evaluated against additional data, especially the flow rates and pressures determined from the PFL measurements (Komulainen et al. 2023).

Current status

A contract is currently in the preparation stage for the respective modelling activities, which will use data obtained from the modelling of Bukov URF II via the PFL method (Komulainen et al. 2023), OBI and ABI (Bukovská et al. 2022), the documentation of the corridor walls and the geophysical measurements that are being taken on a continuous basis during the excavation of the Bukov URF II complex.

6.2.4 Uncertainties concerning in-situ transport parameters

Links to the DGR programme

Due to the limited option for the detailed direct observation of the processes underway at the depth of the future DGR, transport models will always be burdened with a significant degree of uncertainty, concerning which (not necessarily in connection with the DGR) the development of methods for the evaluation of the propagation of uncertainties, whether concerning the input parameter values or the introduction of parameters and the results of observations into the model, has been underway for several years. In connection with the DGR programme, the need arises to systematically develop and implement approaches that allow for the reduction, or at least the quantitative evaluation, of the uncertainties inherent in the transport models. The Bukov URF provides an environment which, due to the possibility of the direct observation of the rock mass, allows for the validation of uncertainty assessment approaches for the conversion of experimental results into parameters that can be used for modelling purposes.

Objectives

- The demonstration of the uncertainties inherent in the evaluation procedure concerning the transfer of in-situ measurement data to the modelling process that can also be used by other research teams and projects.
- The evaluation of the propagation of the uncertainties of individual input parameters and the prioritisation of transport parameters for the migration models.
- The practical implementation of the results of the project when transferring data (which is always burdened with uncertainties) from geological survey work and other research to radionuclide transport models.

Research approach

The first stage will involve the creation of a predictive transport model, concerning which uncertain input values will be entered as a probability distribution function, and the mapping of the range and extent of these uncertainties. The model will be created for a range of relevant transport scenarios (e.g. the transport of conservative substances, sorbent substances, etc.). The model will take into account the variances inherent in the stochastic nature of the model with the indication of the development of the inherent uncertainties. It will be necessary to obtain experimental samples employing an approach that reflects the potential for sampling and monitoring expected at the candidate sites as supplemented by the laboratory assessment of the samples.

The next phase will include the refinement of the model so as to reduce the uncertainties (probability distribution) inherent in the input parameters, e.g. via the application of real measurement data. The predictions provided by the resulting model will then be verified against the results of a stand-alone tracer experiment to be conducted at the Bukov URF. The documentability of the experiment will be more important to the functioning of the modelling approach than its complexity. The model will subsequently be validated against pre-defined monitored values. If the project is successful, it will be followed by another project that considers a more complex system and at a larger scale.

Current status

Preparation stage.

6.2.5 Flow in EDZ and EIZ

Links to the DGR programme

It is assumed that the flow of water and the transport of substances will be affected by the excavation of the transport corridors and disposal wells at the DGR site due to increases in the permeability of the rock in the vicinity of the corridors as a result of the creation of EDZ and EIZ. Therefore, it will be necessary to conduct research that confirms or refutes the impacts of EDZ and EIZ on flow, including the incorporation of the results into the transport models.

Objectives

- The verification of a methodology for the modelling of the influence on the hydraulics of mechanical changes caused by the excavation of underground corridors using the results of in-situ measurement campaigns at the Bukov URF, and the subsequent application of the methodology to the creation of a transport model that takes into account the conditions of the finally selected Czech DGR site and the disposal concept.
- The design and construction of an in-situ experiment aimed at obtaining data on, and evaluating changes in, the pore pressures and hydraulic conductivity in the vicinity of the selected corridor using instrumented boreholes.

Research approach

The research programme will involve the research of core boreholes aimed at obtaining information on the pore pressures of the groundwater in the Bukov URF II rock mass and their development following the excavation of nearby underground passages. Borehole water pressure tests will be performed and evaluated, as will changes in the hydraulic conductivity of the monitored sections of the boreholes before and after the excavation of the respective underground passage. The design of the in-situ experiment is based on experience obtained from the TSX experiment conducted at the Whiteshell URL (Rutqvist et al. 2009) and the GREET experiments at the Mizunami URL (Iwatsuki et al. 2019).

The in-situ experimental programme will provide datasets for the mathematical modelling of EDZ and EIZ. Modelling will include the creation of an inverse hydro-mechanical model, which will be verified against data provided by the monitoring of the development of pore pressure during excavation work and other hydraulic data (flows).

Current status

The contract for the conducting of the in-situ experiment and the associated modelling activities is currently in the preparation stage.

6.3 Testing the construction and characterisation of disposal wells

Links to the DGR programme

The current Czech DGR concept envisages the emplacement of WDP containing SNF in vertical or horizontal disposal wells. The excavation technology and the locations of these large-profile boreholes must first be tested and adapted to the specific needs of the finally-selected disposal concept. The Bukov URF experimental plan reflects the need for experiments for the research of the propagation of heat (chapter 6.4.3), the testing of the engineered barriers (chapters 6.4.5 and 6.4.6) involving the creation of physical models of disposal spaces, and the verification of the method selected for the drilling of large-profile boreholes under DGR conditions.

Objectives

- The drilling of vertical (and possibly horizontal) boreholes for the placement of models of the WDP according to the disposal concept currently considered for the Czech DGR, preferably at the real scale.
- The verification of the technological and rock characterisation approaches to the selection of locations for the DGR disposal wells and the drilling process itself, and the evaluation of the accuracy and quality of the construction of the experimental boreholes.
- The testing of borehole characterisation methods for the evaluation of the accuracy of construction and methods for the mapping of the surfaces of boreholes, the determination of the extent of the damaged zone around the boreholes, and the testing of methods for the monitoring of the flow of water into boreholes.

Research approach

It is assumed that newly-excavated corridors in Bukov URF II will be used for the conducting of the tests. The Rock Block Classification system developed as part of the Characterisation II project will be applied for the site selection and characterisation research. The main priority will concern the drilling of the vertical disposal boreholes. The first phase of the work will comprise the preparation of the test corridor – the clearing of the loose soil and the detailed mapping of all the surfaces of the corridor, followed by the siting of the drilling work and the creation of a predictive DFN model of the rock block. In terms of dimensions, it is assumed that the boreholes will have a diameter of 1650 mm (as planned for the DGR disposal wells); however, the depth is likely to be less than that envisaged for the DGR vertical disposal wells. The decision will depend on the conditions and the technology employed given the dimensions of the Bukov URF II corridors (width and height 4.0 m). Following the drilling of the boreholes, they will be subjected to a quality evaluation, the surfaces will be mapped and the DFN model updated. The monitoring of the groundwater inflows will commence using tried and tested methods immediately following the drilling of the boreholes.

The boreholes will also be available for use in connection with other research activities, for example, as a model disposal site for visual presentations to the public, and, primarily for the conducting of other engineered barrier-related experiments.

Current status

Based on a market consultation approach, the technological and financial conditions will be determined pertaining to currently available technologies for large-profile drilling work. A contract will then be prepared for the conducting of the experiment.

6.4 DGR engineered barriers

This research area addresses, for example, the compatibility of the DGR structural materials (e.g. concrete and grouting and anchoring materials) with the disposal system materials (filling/backfilling materials, WDP components). The basic requirement of all the materials used in the DGR is that they do not interact with each other to such an extent that it could endanger their individual functions and thus the overall safety of the DGR. Currently, the issue of the use of low pH concrete is being addressed (chapter 6.4.1). Furthermore, a new project termed "Long-term laboratory" is in the preparation stage (chapter 6.4.2), the purpose of which will be to provide support for the conducting of further in-situ experiments. Research will also consider the form of the filling/backfilling materials (bentonite pellets and/or compacted bentonite blocks).

The corrosion experiment described in chapter 5.4 addresses the research of the materials to be used for the construction of the waste disposal package, the basic concept of which was addressed as part of the Research and development of a waste disposal package for the deep geological disposal of spent nuclear fuel up to the sample realisation stage project (Forman et al. 2021). A supplementary research project will be considered if deemed necessary based on the results of the corrosion pilot in-situ testing.

This research area also includes experiments connected to the Fillings project (Svoboda et al. 2023), i.e. the HEAT (chapter 6.4.3), ERO (chapter 6.4.4), EXP (chapter 6.4.5) and DEMO (chapter 6.4.6) experiments.

A planned separate research area dedicated to the development and testing of a heater for the simulation of the SNF in the WDP has been removed from the research plan. Rather than comprising a separate issue, it will form part of other planned experiments (e.g. HEAT).

6.4.1 Low pH concrete

Links to the DGR programme

It is assumed that concrete will be used as one of the construction materials in the DGR, e.g. for stabilising the underground corridors or for the sealing plugs of the disposal and access corridors. Aimed at reducing the risk of negatively impacting the properties of the bentonite via interactions with concrete, research in this area is concerned with the development and testing of reduced-pH concrete mixtures (pH equal to or lower than approx. 11). A SÚRAO pilot project that focused on the development of a mixture of concrete and mortar with a reduced pH was concluded in 2019 (Pernicová et al. 2019).

Objectives

- The verification of the long-term stability of a newly-developed concrete with reduced pH.
- The verification of the potential use of the proposed material in underground constructions at the larger scale (cast and sprayed concrete and/or injection material).

Research approach

The first phase will include the assessment of a previously designed sprayed concrete mixture, based on which the decision will be made as to whether any further adjustments should be made to the formula. The application of the concrete mixture will first be tested under controlled conditions on the surface, and after attaining the required performance level, the application of the material will be tested under underground conditions. Samples will be taken from the applied material at given time intervals for laboratory analysis, concerning mainly the mechanical properties and the pH. Moreover, the proposed mixture will also have to be adjusted so as to meet the strict requirements for structural concrete in underground structures. A follow-up project will focus on the development and testing of a low pH injection compound (grout). This research area will include the testing of other selected injection mixtures for improving the quality of the rock environment and the sealing of boreholes.

Current status

A SÚRAO project that focused on the development of a mixture of concrete and mortar with reduced pH was concluded in 2019 (Pernicová et al. 2019). The first part of the project concerned the development of a formula for cast concrete, which was concluded by the industrial production of 1 m^3 of the material from which test samples were taken. These samples are stored at the Bukov URF and are being tested on a continuous basis aimed at verifying the stability of their mechanical properties when exposed to underground conditions (high humidity). The second part of the project involved the pilot testing of the sprayability of the mixture, the formula for which was modified especially for application via spraying (Čítek et al. 2020); the test yielded acceptable results. As with the cast concrete samples, samples of the sprayed concrete (obtained via core drilling) are being subjected to the laboratory analysis of their physical and mechanical properties.

Further mixtures for the production of sprayed and cast concrete were prepared in 2023. Sprayed concrete was successfully applied to stabilise the ceiling of laboratory corridor L7 in Bukov URF II. It is planned that the cast concrete will be used for the construction of support pillars at the intersections of the L7 laboratory corridor and selected test chambers.

6.4.2 Long-term laboratory

Links to the DGR programme

The project involves the creation of a collection of reference samples of the various candidate materials for the DGR engineered barriers and other construction materials and their storage under various conditions and combinations for the study of their long-term behaviour and interactions. Moreover, a further aim is to ensure that a sufficient supply of materials is available for the potential future analysis of the materials in connection with the conducting of future in-situ experiments.

Objectives

- The evaluation of the natural ageing of reference materials stored in air at the Bukov URF using comparative samples exposed to the same degree of environmental influence.
- The determination of the properties of the environment that exert direct or indirect impacts on the materials and their natural (and artificial) interactions.
- The characterisation and analysis of the input materials and the subsequent comparison of the affected materials at predetermined time intervals from the start of the experiment.

- The evaluation of the interactions that take place between the materials and the environment (in the air or in boreholes in the Bukov URF).
- The preservation of a stock of long-term affected reference materials in boreholes with the potential for their possible further experimental use.

Research approach

The first part of the project is concerned with the storage of structural and filling materials that have been subjected to testing in other projects both under air conditions in the Bukov URF and in inert containers without the potential for interaction with other materials so as to exclude the impacts of the Bukov URF environment on their properties. The stored materials include concrete with reduced pH and normal concrete, metal reinforcement components, injection materials (organic and mineral), bentonite in various forms (powder, pellets, compacted blocks, suspensions) and aggregate for the production of concrete samples. Regular sampling and laboratory analysis is planned on an ongoing basis.

A supplementary project, the conducting of which is not directly linked to the Bukov URF environment, includes the study of the interactions of materials stored in containers under both anaerobic and aerobic conditions. For example, the anaerobic interactions of materials in bentonite suspensions and the simulation of bentonite ageing via contact with synthetic groundwater with a high cation content under thermal loading conditions.

A series of boreholes in the Bukov URF filled with the various materials of interest will be used to monitor interactions with the rock mass and the impacts on the materials. Vertical boreholes with a diameter of 150 mm will be filled with the reference materials in predetermined combinations. The materials will not be heated and will be exposed to natural groundwater saturation. Another experiment will involve the storage of materials in metal perforated modules (Fig. 33) that will allow for artificial groundwater saturation and, possibly, heating. The modular system will allow for the ongoing extraction of the samples.

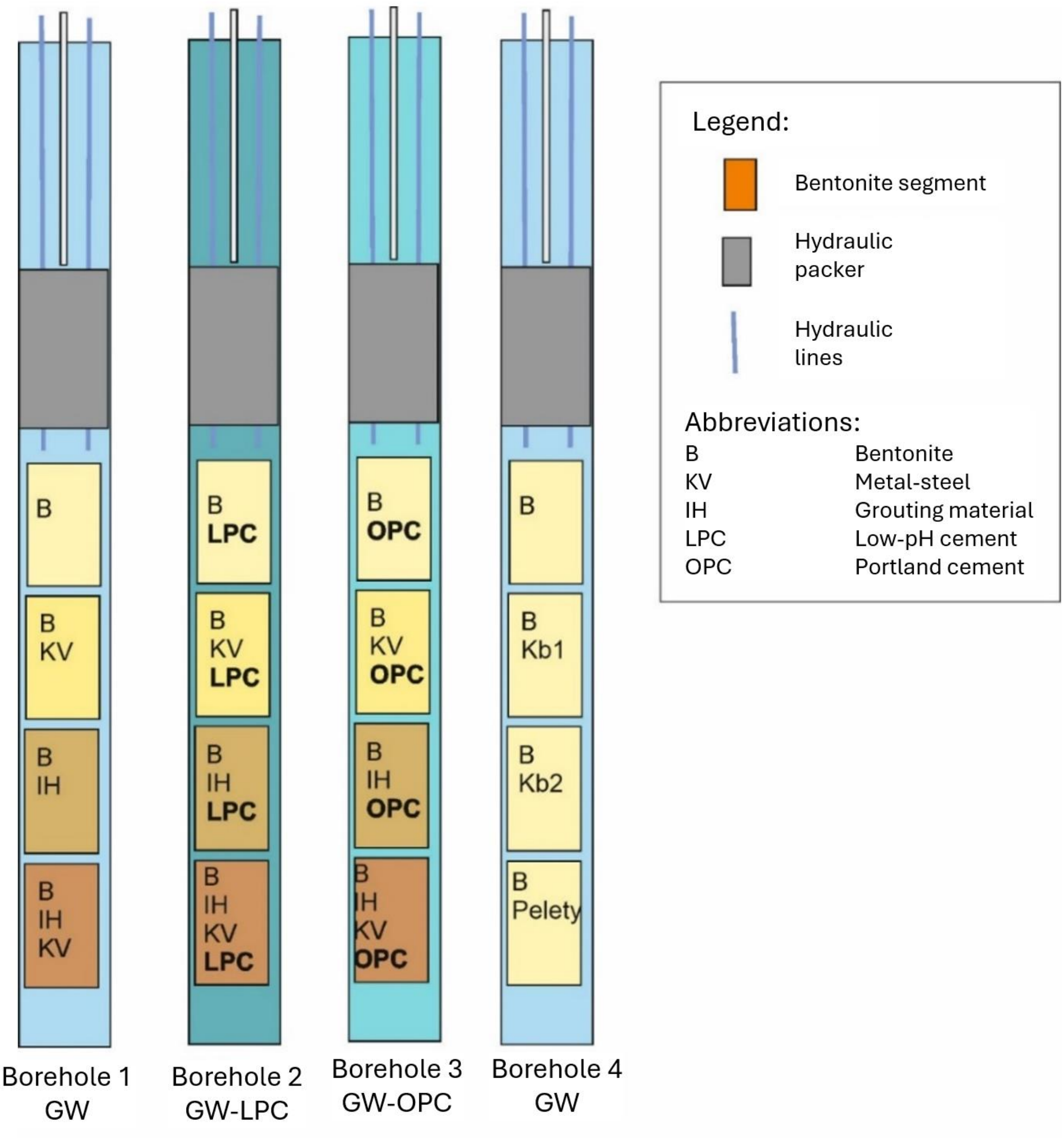

Fig. 33 – Design of the modules for the storage of unheated materials in vertical boreholes

Current status

A detailed description of the recommended technical approach is provided in a report that sets out recommendations for experiments related to the development of the DGR engineered barriers (Svoboda et al. 2023).

6.4.3 Experimental study of THM(C) processes – HEAT experiment

Links to the DGR programme

The requirement for the conducting of this experiment is based on the long-term safety section of the SÚRAO 2020 R&D Plan in accordance with the requirements of Decree No. 377/2016 Coll. on the verification and validation of THMC models of the development of the DGR engineered barriers - specifically objectives nos. 3 and 6 of the SÚRAO 2020 R&D Plan, namely:

- The verification of the dissemination of temperature in the DGR using sources that simulate the SNF;
- The verification of the prediction of THMC processes under real repository conditions.

The project is concerned primarily with the modelling of the propagation of heat, the temperature development, moisture distribution and mechanical response, i.e. THM processes, potentially accompanied by the consideration of chemical processes (C).

Objectives

- The verification of the behaviour of the bentonite barrier under DGR conditions with the possible comparison of several technical design solutions.
- The experimental verification of the propagation of heat from the WDP through the bentonite barrier and into the rock mass.
- The acquisition of data for the validation of mathematical models concerned with the simulation of the processes underway in the disposal and surrounding areas during the period in which the filling materials become saturated.
- The acquisition of data for the validation of the mathematical models to be employed for the thermal dimensioning of the DGR.
- The verification of the extent of the DGR area and the updating of cost estimates.

Research approach

The project includes the construction and operation of physical models of the bentonite barrier with heaters that will simulate the SNF in the WDPs in the DGR. The construction is assumed of several physical models of the fillings of the disposal wells (buffer; Fig. 34) thermally loaded as under DGR conditions. The models will differ in terms of both their technical design and the extent of monitoring instrumentation. The data obtained from the in-situ experiments will be used for the calibration and validation of mathematical models. The scale of the physical models compared to the real buffer components planned for the DGR and the monitoring systems will be decided based on the requirements of mathematical modelling specialists. The preferred scale of the models is as close as possible to the real situation in the DGR. The experiment will include the monitoring of the temperature, humidity and total stress/strain in the physical models and in the surrounding rock mass. Each of the physical models will have its own monitoring system based on the specific experimental objectives.

The following inputs will be required for the conducting of the experiment:

- A specially designed and tested heater.
- The results of mathematical THM modelling (the Fillings project).
- Large-profile boreholes for the emplacement of the physical models (chapter 6.3).

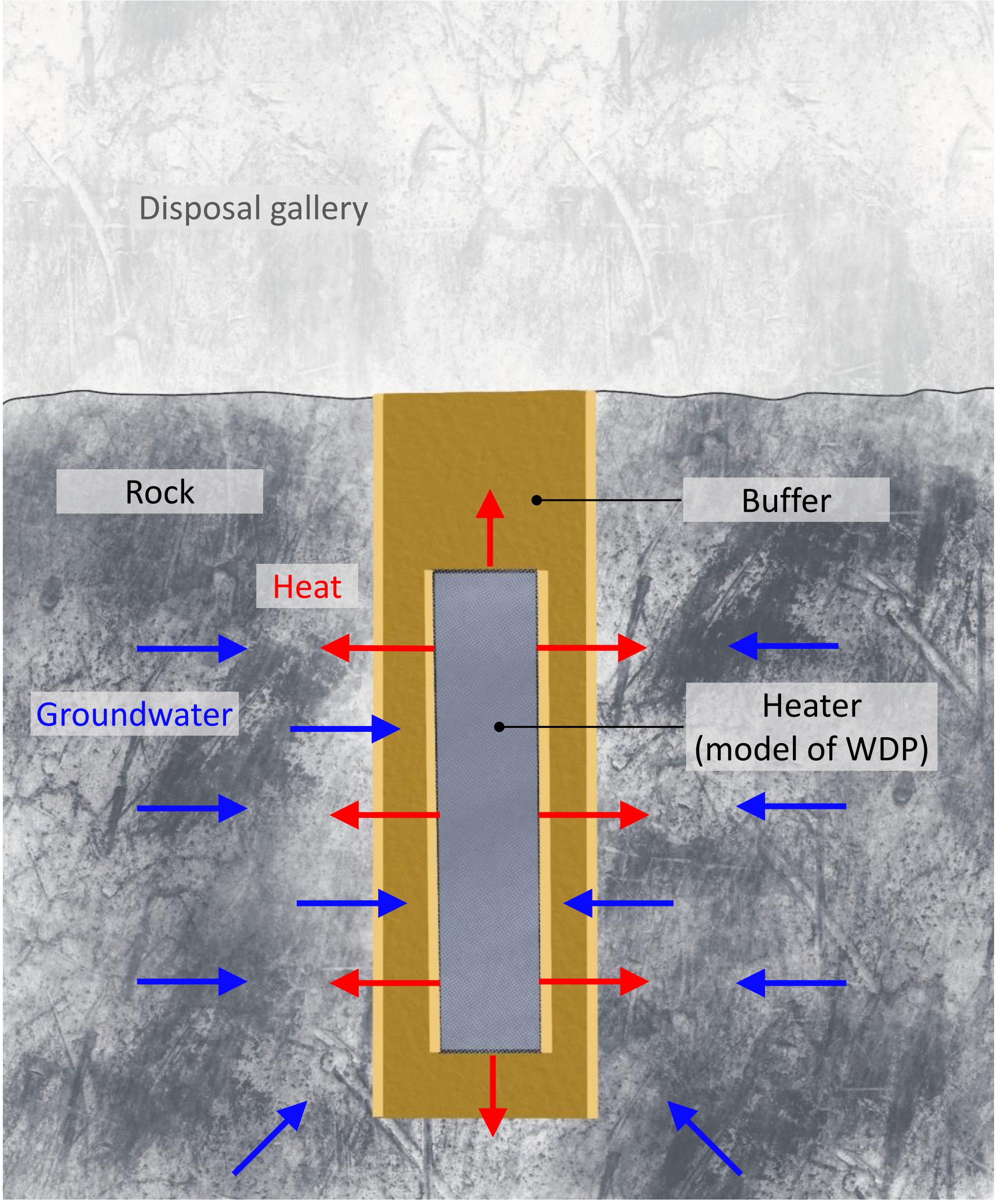

Fig. 34 – Illustration of a physical model of a disposal package – vertical disposal option

Current status

The first in-situ experiment included in this research area comprises the Interaction experiment underway in the Bukov URF I complex. Although the main aims of the project are not primarily concerned with the study of the propagation of heat, a certain amount of information has been obtained in this respect. The network of temperature sensors emplaced in the bentonite filling of the heated physical models and in the surrounding rock is providing information on the spread of temperature during the loading phase of the experiment, which has been underway since 2019. Although the layout and dimensions of the experiment do not allow for the provision of information that is directly applicable to the real scale of the DGR disposal spaces, the experiment is providing data for the validation and verification of the related mathematical models.

The next stage in this research area concerns the conducting of the “HEAT” experiment, the proposed technical design of which involves the construction of a disposal space model with real-size borehole diameters (1650 mm) and a model of the WDP (914 mm). The experiment includes the placement of a central heater (to simulate the SNF in the WDP) in a large-profile vertical borehole partially surrounded by a buffer and the installation of several heaters in smaller diameter boreholes in the vicinity (Fig. 35). The heater in the central borehole will be divided into several sections to allow for the simulation of various thermal scenarios and will be controlled according to a constant temperature on the surface of the heater or according to the power. The purpose of the small-profile boreholes will be to simulate the impact of the thermal fields emitted by nearby WDPs on the central WDP model. The monitoring of the experiment will focus mainly on the distribution of heat. The project envisages the conducting of multiple phases of the experiment at the one site with the potential for the replacement of the bentonite filling with bentonite with differing initial moisture contents. The bentonite filling will be removed after each phase and subjected to laboratory analysis (the determination of the moisture content, dry density, thermal conductivity and capacity). The individual scenarios/phases will be designed based on preliminary numerical simulations.

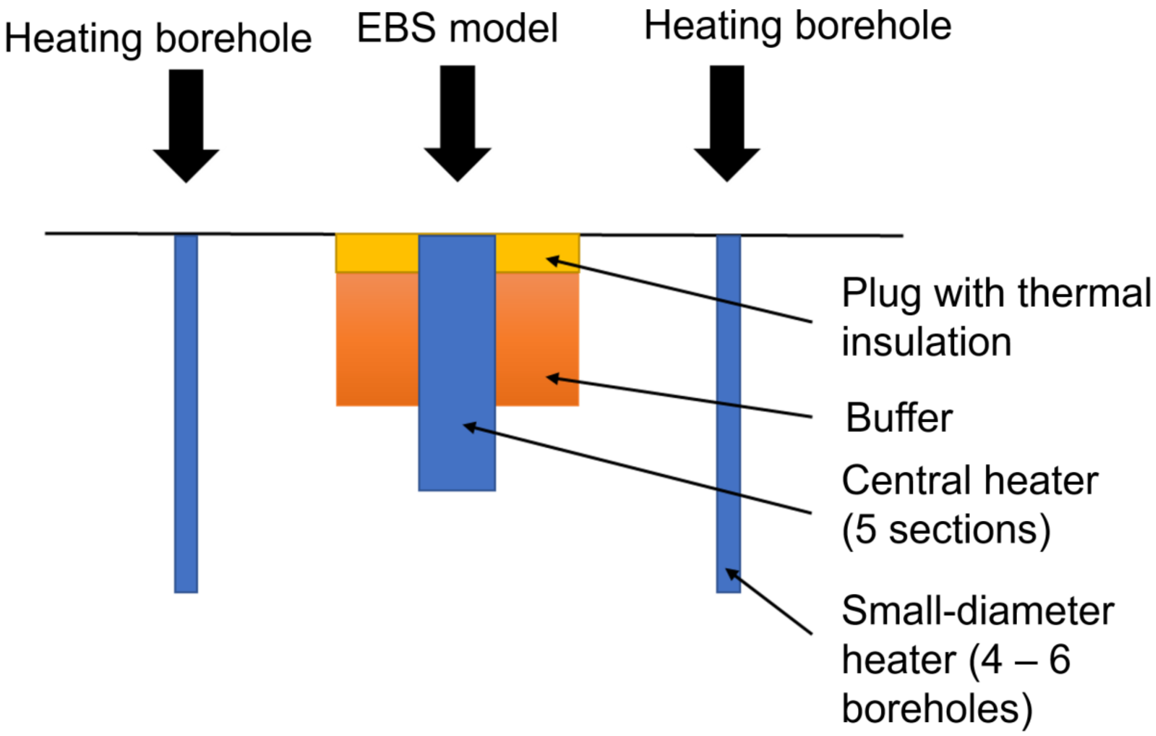

Fig. 35 – Scheme of the HEAT experiment (Svoboda et al. 2023)

6.4.4 Bentonite erosion and colloid transport (ERO)

Links to the DGR programme

The potential threats to the bentonite barriers of the DGR include the erosion of the bentonite filling material. The advective flow of water in the fracture systems of the host rock could lead to mechanical and chemical erosion, and thus the partial degradation of the bentonite barriers. In addition to the deterioration of the sealing ability of the bentonite, the risk exists of the formation of colloids, which could significantly impact the transport of substances from the DGR. Colloid transport potentially comprises the main mechanism for long-distance migration, especially with concern to strongly sorbing radionuclides. Thus the verification of the behaviour of the candidate Ca-Mg bentonite is of key importance for the Czech DGR concept.

Objectives

- The determination of the rate and velocity of the erosion of the bentonite barrier due to advective flow in the fracture systems of the host rock with concern to Czech Ca-Mg bentonite.
- The evaluation of the stability and sealing abilities of bentonite and the determination of the conditions required for the formation of colloidal particles in the rock mass.

Research approach

The proposed ERO in-situ experiment (Svoboda et al. 2023) involves the preparation of a site for the drilling of three core boreholes (diameter 90 mm and length 5-10 m) that traverse a discrete hydraulically conductive fracture (fracture zone). The boreholes will be equipped with double packers to isolate the fractured sections of the boreholes. Bentonite blocks will be emplaced in the central borehole (Fig. 36). The first phase of the experiment will concern the study of the erosion of bentonite and the release of bentonite colloids. The circulation of water in the fracture system that erodes the bentonite will be ensured between the boreholes. Following the loading phase, a sample of the bentonite will be extracted from the borehole for laboratory analysis. The second phase will include the conducting of tracer tests; the tracer will be injected so that it passes through the bentonite filling into the fracture zone. The related modelling part of the project will be aimed at evaluating the impact of the presence of bentonite on the transport of the selected tracer. The use of radioactive tracers is being considered in the final phase of the experiment to allow for the monitoring of sorption into the bentonite.

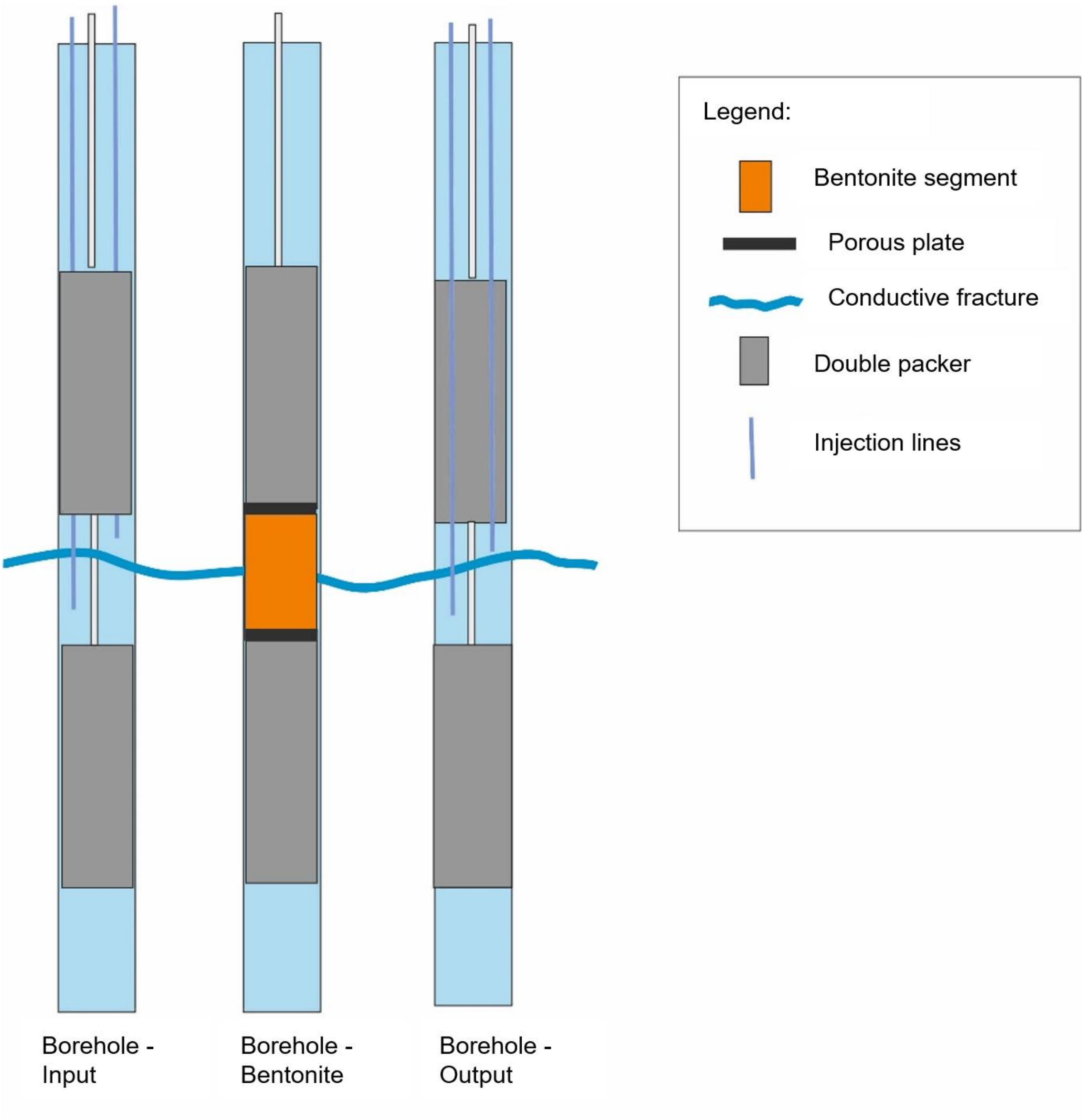

Fig. 36 – Conceptual design of the bentonite seal erosion experiment (Svoboda et al. 2023)

Current status

A detailed description of the recommended technical design is provided in a report that outlines recommendations for experiments related to the development of the DGR engineered barriers (Svoboda et al. 2023).

6.4.5 Buffer expansion into the backfill and WDP loading (EXP)

Links to the DGR programme

The vertical disposal concept envisages the use of a spacer block made of bentonite, which will serve as the plug for the disposal wells. The study of this component of the disposal system revealed the current lack of knowledge on the behaviour of the contact area between the filling material of the disposal wells and the backfilling of the disposal corridors. The main problem relates to the differing dry densities of the two bentonite components, which could impact the mechanical behaviour of the whole of the DGR disposal horizon. A further area of research to be addressed concerns the mechanical loading of the WDP, which may be affected by differing buffer saturation scenarios.

Objectives

- The design and conducting of an in-situ experiment employing a vertical model of a disposal space, including the adjacent part of the disposal corridor.
- The verification of WDP, buffer, spacer block and backfill installation techniques.
- The determination of the dimensions and design of the spacer block.
- The verification of the mechanical stress acting on the WDP due to the swelling of the bentonite according to various buffer saturation scenarios.

Research approach

The technical design of the experiment is based on the vertical disposal concept. A simplified diagram of the experiment is shown in Fig. 37. The vertical borehole will have a diameter of 1.65 m (as envisaged for the DGR) and a depth as close as possible to that anticipated for the DGR disposal wells (the depth of the borehole will depend on the selected drilling technology and the dimensions and layout of the Bukov URF II corridors). The model of the WDP (with dimensions and weight as close as possible to the parameters of the WDP for VVER 440 SNF) will be emplaced in the borehole (for simplification purposes without a heating element) and surrounded by a bentonite filling (buffer and spacer blocks). The corridor will be backfilled and sealed with a removable steel plug.

Both the corridor and the borehole will be equipped with saturation and monitoring portals at selected locations that will be used depending on the test scenario for the injection of water, the monitoring of the pore water pressure or the monitoring of outflows with the potential detection of bentonite erosion. The monitoring of the position of, and the stress acting upon, the WDP model and the monitoring of the development of bentonite saturation will comprise important parts of the experiment.

Several experimental scenarios with differing saturation regimes that lead to the uneven swelling of the bentonite are envisaged. For example, saturation from the bottom upwards, which is expected to cause the upward shifting of the WDP, saturation in the upper level of the WDP and the simulation of high water inflows into the backfill that leads to the erosion of the bentonite.

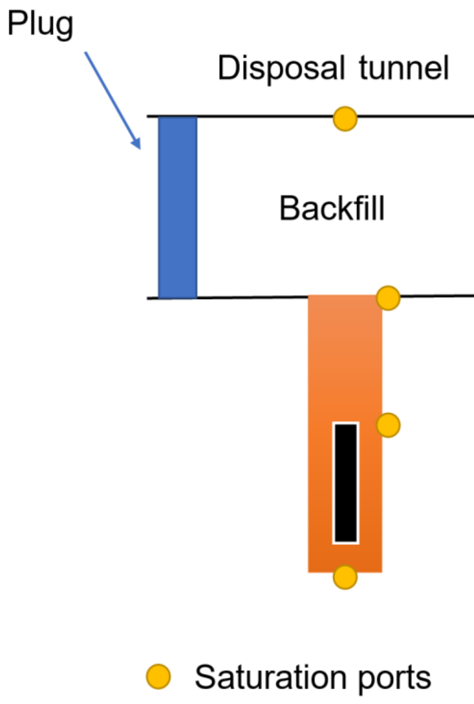

Fig. 37 – Scheme of the EXP experiment (Svoboda et al. 2023)

Current status

The basic technical approach to the experiment has been determined. This experiment comprises an important preliminary stage of the demonstration experiment, and the experimental location/setup may also eventually be used for this experiment.

6.4.6 Demonstration experiment of a prototype repository (DEMO)

Links to the DGR programme

The Czech DGR project is based on the in-time preparation of a Czech technical design solution and the testing thereof under the appropriate conditions at the appropriate depth below the surface even before work commences at the selected final site for the DGR. The primary aim of the Bukov URF programme concerns the demonstration of the feasibility and functionality of the considered technical approaches to the construction of the DGR.

Objectives

- The demonstration of the technical feasibility of the DGR concept.
- The demonstration of the functionality of the concept (the long-term operation of the experiment with the monitoring thereof).
- The verification of the stability of the materials used.

Research approach

The project will include the construction of a model of a selected section of the DGR based on the synthesis of the knowledge acquired from previous projects, and at a time at which the disposal concept will have been more precisely defined. The end section of one of the experimental corridors at the Bukov URF is expected to be used for the construction of the prototype repository.

The demonstration of a vertical WDP disposal system is currently the favoured option. A more detailed description of the "DEMO" experiment is provided in report 684/2023. The experiment will involve the preparation of several disposal boreholes at distances from each other that correspond to those planned for the DGR. The models of the WDPs fitted with heaters, along with the bentonite fillings (buffer) and spacer blocks, will be emplaced in the disposal boreholes. The disposal corridor will then be backfilled and sealed with a concrete plug. The experiment will include the fitting of instrumentation for the monitoring of the behaviour of the various engineered barrier components and the host rock. Fig. 38 shows a simplified diagram of the design of the demonstration experiment. It will comprise a total of 3 vertical disposal boreholes containing models of the WDP, each of which will simulate different DGR development scenarios (in terms of the saturation of the buffer).

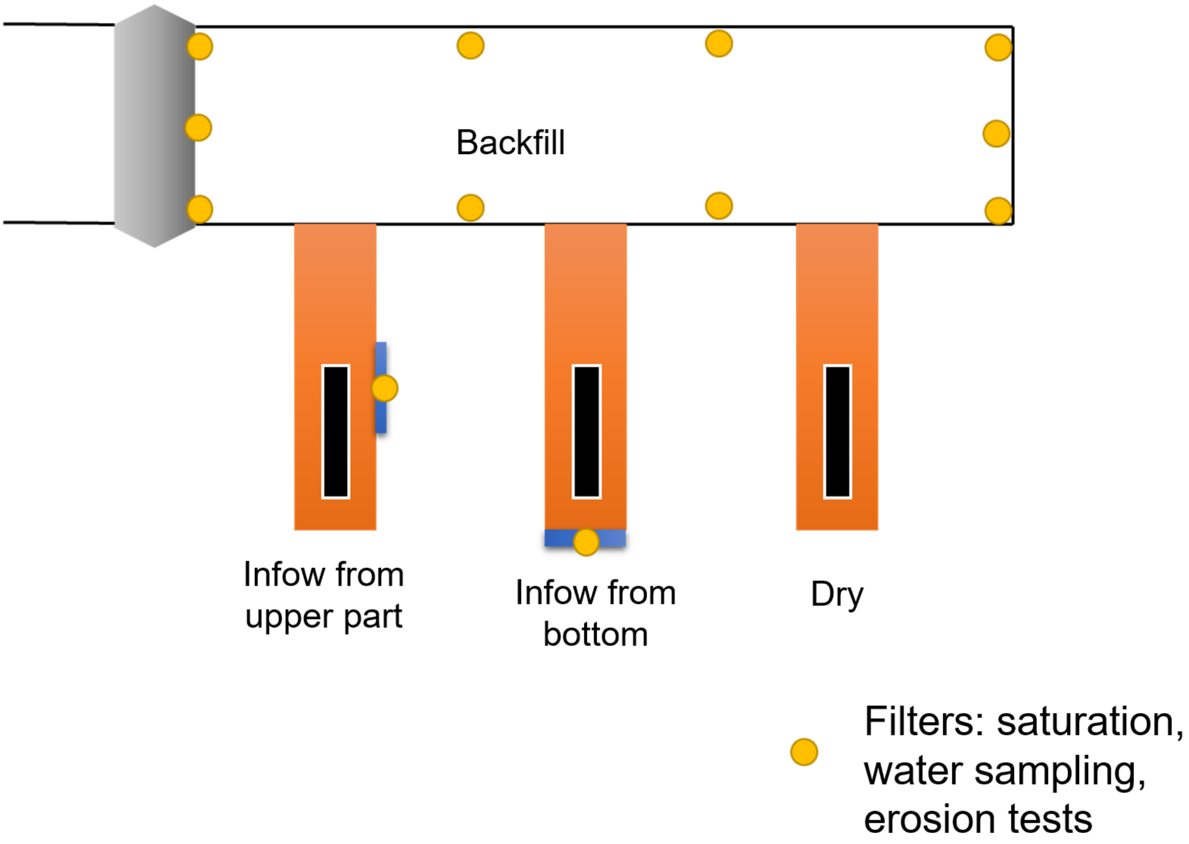

Fig. 38 – Scheme of the demonstration experiment (Svoboda et al. 2023)

Fig. 39 shows a sample cross-section of a DGR disposal space for the currently considered vertical disposal option in a conventionally excavated tunnel. The demonstration experiment will be designed so that the dimensions are as close as possible to those of the dimensions assumed for the DGR, i.e. so that the dimensions and distances correspond proportionally to the disposal spaces of the DGR taking into account the spatial and technological conditions in the Bukov URF. For example, a shorter length WDP model is assumed due to the lower heights of the corridors in the Bukov URF, etc.

Current status

The basic technical design of the demonstration experiment for the vertical disposal system has been determined. Since this experiment will comprise the culmination of the Bukov URF research programme, it must be preceded by the successful conclusion of the various experiments concerning the development of the engineered barriers (HEAT, EXP, ...) and the development and testing of the WDP model handling and filling installation techniques.

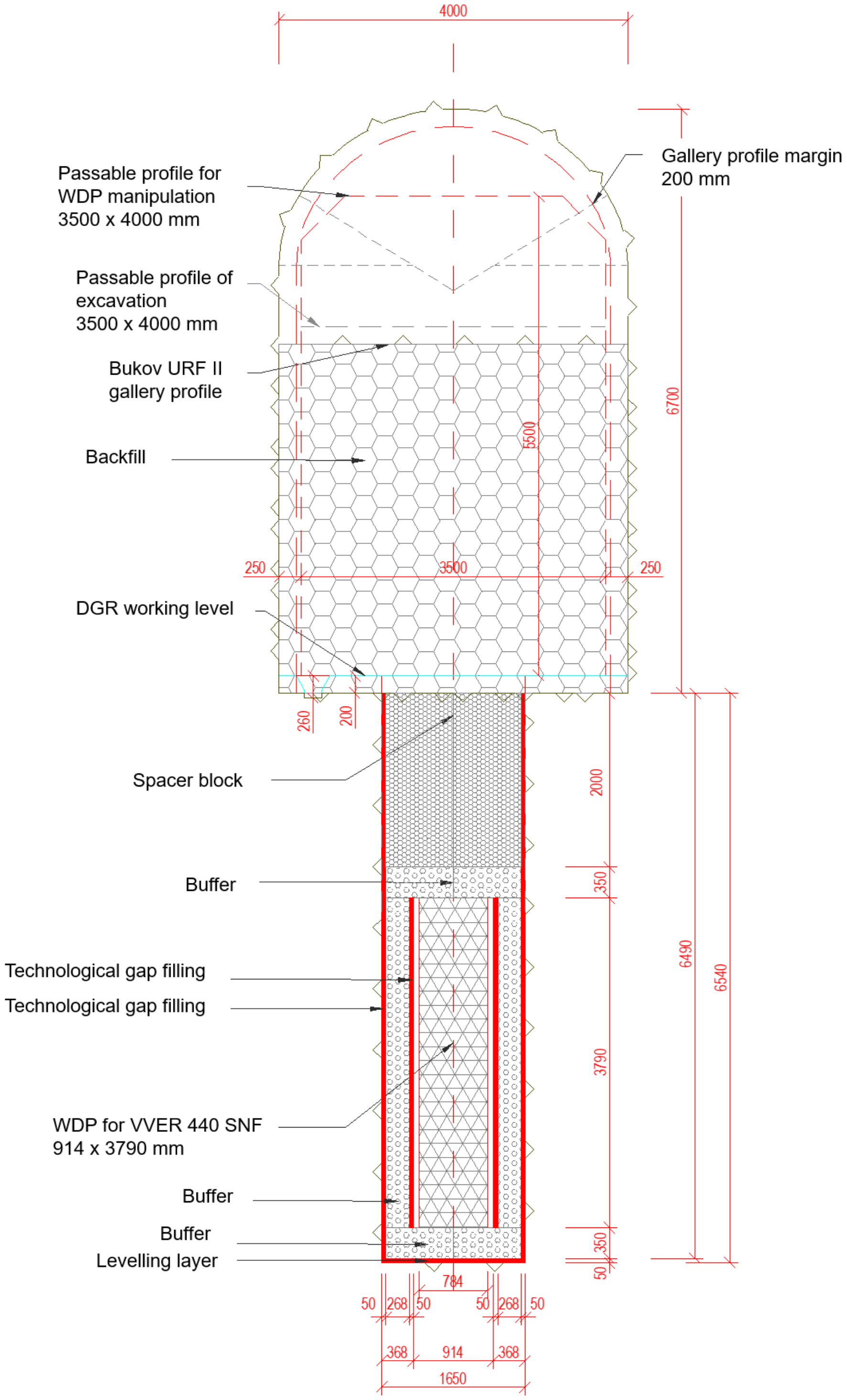

Fig. 39 – Section through a DGR disposal space (Svoboda et al. 2023)

7 Conclusion

This SÚRAO strategic document provides a summary of completed, ongoing and planned activities at the Bukov URF in the form of an update to the first version of the document (2021). The level of detail provided in the descriptions of the experiments and projects corresponds to the current state of readiness of the DGR programme. The Bukov URF provides a unique opportunity to obtain data for the creation, validation and verification of the mathematical modelling tools required for the successful implementation of the Czech DGR project. The investment in the improvement of the Bukov URF infrastructure and the excavation of the Bukov URF II section have provided the additional laboratory capacity required to successfully fulfil the experimental plan.

New projects are currently in the preparation stage, most of which will address long-term interactions between the materials to be used in the DGR and the environmental impacts on these materials. One of the key priorities is to resolve the issue of the construction of large-profile boreholes, the realisation of which is the principle condition for the emplacement of in-situ physical models of the DGR disposal spaces at a scale that best reflects the real dimensions of the future DGR. One of the main research topics concerns the verification of the propagation of heat from the WDP through the bentonite buffer and into the rock mass. Moreover, it is planned that the study of the mechanisms of the transport of substances through fracture systems and the engineered barriers will continue. This document will be further updated in the future as required so that it accurately reflects the development of the Czech DGR development programme and, in general, the development of science and research in the field of the deep geological disposal of RAW. It is possible that the basic research programme described in this document will be supplemented by other experiments according to the recommendations provided in external studies, provided they are considered to be beneficial to the Czech DGR development programme.

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