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SÚRAO RESEARCH & DEVELOPMENT PLAN 2024-2028

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SÚRAO

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Contents

List of abbreviations

ACED Assessment of the Chemical Evolution of ILW and HLW Disposal Cells (Sub-project of the EURAD programme)

B(U)F Radioactive shipment type B, (U) – unilaterally approved by the competent authority of the country of origin of the design type, F – content of fission products

BPEJ Certified soil ecological unit

ČBÚ Czech Mining Authority

CEC Cation exchange capacity

ČEZ ČEZ, a.s. (Czech power company)

ČHMÚ Czech Hydrometeorological Institute

CIM Carbon – Iodine Migration (a project conducted at the Grimsel underground laboratory that focused on the migration of carbon and iodine)

CMIC Chemical microbial influenced corrosion

CONCORD CONtainer CORrosion under Disposal conditions (Sub-project of the EURAD programme - Assessment of container corrosion under DGR conditions)

ČVUT FJFI Czech Technical University, Faculty of Nuclear and Physical Engineering

D&B Drilling and Blasting (blasting work)

DB Design basis

DECOVALEX DEvelopment of COupled models and their VALidation against EXperiments – An international project that focused on the development and validation of models of processes that take place in DGRs

DFN Discrete fracture network

DGR Deep geological repository

DIAMO A state-owned company, with headquarters in Stráž pod Ralskem, for the remediation of the consequences of mining activities following the extraction of uranium

DONUT Development and Improvement of Numerical methods and Tools for modelling coupled processes (sub-project of the EURAD programme)

DOPAS – EPSP Full-Scale Demonstration Of Plugs And Seals – Experimental Pressure and Sealing Plug (European project that focused on the design of plugs for the needs of DGRs. The Czech plug experiment (EPSP) was conducted at the Josef underground laboratory)

EBS Engineered barrier system

EDU Dukovany nuclear power plant

EDZ	Excavated damaged zone
EdZ	Excavated disturbed zone
Eh	Redox potential of a system or environment
EIA	Environmental impact assessment
EMIC	Electrical microbial influenced corrosion
ETE	Temelín nuclear power plant
EURAD	European Joint Programme on Radioactive Waste Management (Homepage | Eurad (ejp-eurad.eu))
FEP	Features, events and processes
GAS	Mechanistic understanding of gas transport in clay materials (sub-project of the EURAD programme)
GPS	Global positioning system
HITEC	Influence of temperature on clay-based material behaviour (sub-project of the EURAD programme)
HLW	High-level waste
HotBent	Hot Bentonite (international project on the behaviour and properties of bentonite above 100°C) - a full-scale experiment conducted at the Grimsel Test Site (GTS), Switzerland
IAEA	International Atomic Energy Agency
ICRP	Internal Commission on Radiological Protection
IGD-TP	Implementing Geological Disposal for Radioactive Waste – Technology Platform (International technological platform for the geological disposal of radioactive waste) Implementing Geological Disposal for Radioactive Waste – Technology Platform
ILW	Intermediate-level waste
IPPC	Integrated Pollution Prevention and Control
IRS	Ionising radiation source
KBS-3	Swedish concept for the final disposal of spent nuclear fuel based on a combination of three barriers (the waste disposal package, bentonite buffer barrier, host rock)
KMS	Knowledge management system
KTA	Safety standards established by the German Nuclear Safety Standards Commission (from the German Kerntechnischer Ausschuss:)

LLW	Low-level waste
LTD	Long Term Diffusion –A project conducted at the Grimsel underground laboratory aimed at understanding the diffusion of radionuclides into the rock matrix
LVR	Light water research reactor
MACOTE	Material Corrosion Test - an experiment conducted at the Grimsel Test Site (GTS) aimed at understanding the corrosion of materials under deep geological repository conditions
MF ČR	Czech Ministry of Finance
MIC	Microbial influenced corrosion
MPO	Czech Ministry of Industry and Trade
MŠMT	Czech Ministry of Education, Youth and Sports
MZd	Czech Ministry of Health
MŽP	Czech Ministry of the Environment
NAGRA	National Cooperative for the Disposal of Radioactive Waste
NAPRO	National programmes
NEA	Nuclear Energy Agency
NNS	New nuclear sources
NORM	Naturally occurring radioactive materials
NPP	Nuclear power plant
NSRAO	low-level and intermediate-level waste
NV	Government regulation
OS ŠKODA VPVR/M	storage and transport package developed via cooperation between Škoda JS a.s. and ÚJV Řež, a.s.
PDE	equivalent dose
PHARE	Pologne-Hongrie Actions pour la Reconversion Economique (EC aid programme for transforming countries of the former Soviet bloc)
Posiva Solutions	Subsidiary of Posiva
Posiva	Finnish organisation for the management of SNF
PSHA	Probabilistic Seismic Hazard Analysis
QA	Quality assurance
QC	Quality control
R&D	Research and development

RAW	Radioactive waste
REP	Research and experimental plan
RMR	Rock mass rating
ŘSD ČR	Czech highways authority
SEA	Strategic environmental assessment
SFC	Spent fuel calculation (Sub-project of the EURAD programme)
SKB	Swedish organisation for the management of SNF and RAW
SNF	Spent nuclear fuel
SRB	Sulphate-reducing bacteria
SRA	Strategic Research Agenda
SÚJB	State Office for Nuclear Safety
SÚRAO	Czech Radioactive Waste Repository Authority
SŽ	Czech railways administration authority
TAČR	Technological Agency of the Czech republic
TBM	Tunnel boring machine (fully mechanised excavation)
TDS	Total dissolved solids
TENORM	Technologically enhanced naturally occurring radioactive material
THMC	Thermal, hydraulic, mechanical and chemical processes
ÚJV Řež	ÚJV Řež, a.s.
URC	Underground research centre
URF	Underground research facility
VSP	Vertical seismic profiling
VVER	Water-water power reactor
WDP	Waste disposal package
WP	Waste package (depending on the context)
WP	Work package (depending on the context)

Explanation of terms

Assessment of an area for the siting of a nuclear facility

According to Decree No. 378/2016 Coll. the results of the assessment of an area for the siting of a nuclear facility must be compared with the characteristics of the site, the negative results of which prohibit the siting of a nuclear facility. The assessment must include the evaluation of:

a) the simultaneous action and mutual influence of the properties, their intensity and duration,
b) the future development of the characteristics of the area.

Backup site

One backup site will be held in reserve in the case of the occurrence of unforeseen events concerning the detailed characterisation of the final site. The backup site is an alternative site that could be used in the event that it is not possible to locate the DGR at the selected final site for technical, safety, capacity or other reasons.

A proposal for a final site and a proposal for a backup site for the future deep geological repository for radioactive waste and spent nuclear fuel must be submitted to the Government by 31 December 2030.

Category IV workplace

A category IV workplace is, in accordance with Act No. 263/2016 Coll. and its implementing decrees, a workplace with nuclear equipment.

Characteristics of an area that rule out the siting of a nuclear facility

The characteristics of an area that rule out the siting of a deep geological repository according to section 18 of Decree No. 378/2016 Coll. are as follows:

a) a rock environment that enables the migration of radioactive, chemical and toxic substances that could be released from disposed of radioactive waste so that, during the expected development of the deep geological repository, a representative person will be exposed to more radiation than is set by the dose optimisation limit (0.25 mSv per calendar year - section 82, Act No. 263/2016 Coll., the Atomic Act),
b) the impossibility of creating:
   1) a comprehensive spatial model of the geological structure due to the complexity of the geological structure and tectonic conditions,
   2) a hydrogeological model due to the difficulty of describing and predicting the hydrogeological conditions of the area for the siting of the nuclear facility, or
   3) geomechanical and geochemical models of the area for the siting of the nuclear facility, or

c) the presence of geothermal energy sources.

Section 18 of Decree No. 378/2016 Coll. provides a list of the characteristics of the area that need to be evaluated, but does not provide values according to which it would be possible to compare potential areas for the siting of a deep geological repository.

The characteristic of the traversing of an area for the siting of a nuclear device by a fault, upon reaching which the siting of a nuclear facility is prohibited

The characteristics of the traversing of an area for the siting of a deep geological repository by a fault, upon reaching which the siting of a deep geological repository is prohibited according to section 6 of Decree No. 378/2016 Coll. are:

a) the occurrence of a zone of movement or seismically active fault or other movement of the earth's crust, which could lead to the deformation of a nuclear facility thus reducing nuclear safety, within a distance of 5 km,
b) the occurrence of an accompanying fault at the nuclear facility site.

Conservative approach

A method for assessing the influence of uncertainties concerning knowledge, input data, and applied methods and models via the expert estimation or statistical evaluation of the results that includes the least favourable plausible variants.

Decommissioning

Decommissioning is a set of administrative and technical activities aimed at the complete decommissioning of nuclear facilities and category III and IV workplaces with restrictions on their use for other activities related to the use of nuclear energy or activities that include exposure situations.

Deep geological repository (DGR)

A deep geological repository is a nuclear facility that is used for the permanent disposal of radioactive waste at a depth of at least 300 m below the earth's surface so that its location fulfils nuclear safety conditions for the disposal of high-level waste.

Design basis

A set of information, especially assumptions, conditions, requirements, functions, values and states used in the design of nuclear facilities, from which the specific project requirements are derived.

This information contains, in particular, the justification of specific project requirements:

- used for the specification of safety and operational functions and requirements for the properties of systems, structures and components,
- for the solution of assumed states of the nuclear facility (normal operation, abnormal operation and emergency conditions) in relation to the required properties of systems, structures and components,
- for addressing potential internal and external influences and events and their combinations, which could lead to an undesirable change in the state of the nuclear facility, and the resulting requirements for the resistance of systems, structures and components,
- used for specific assumptions and values (acceptability criteria), which represent the limits of the functionality and safety of the project (under which the mentioned functions are fulfilled); must be based on legislation, generally accepted practice and/or must be derived from analyses based on calculations or experiments and on the initial

knowledge and experience of the project supplier, specific assumptions and rules set for the nuclear facility project.

Design requirements

Safety, functional and other requirements for nuclear facilities as based on the relevant project guidelines throughout the various project design stages:

- according to a hierarchical structure for the stage of the nuclear facility (Level 1), systems (Level 2), facility (Level 3), and parts of the facility (Level 4) and the corresponding project baselines in the same hierarchy,
- in general, it concerns the answer to the question **"How"** or **"What"** a nuclear facility must fulfil to ensure that all the relevant design functions are met. It can be fulfilled via a description, graphic or specific parameters with specified numerical limit values, a range, etc.

DGR reference project (design, components, materials)

The DGR reference project (solution, components, materials) comprises the technical design of the DGR considered at a given time to be the most suitable design from the safety concept point of view. The design may change depending on the specific characteristics of the sites and the acquisition of new knowledge.

Effective dose

The effective dose is the sum of the products of tissue weighting factors and the equivalent dose in irradiated tissues or organs; the tissue weighting factor is determined in Appendix 2 of decree No. 422/2016 Coll., on radiation protection and the security of radionuclide sources.

Engineered barrier

A man-made barrier that prevents the transport of radionuclides through, or the loss of the safety functions of, the disposal barriers, for example waste disposal packages and sealing materials.

Final site

A proposal for a final site and a proposal for one backup site for the future deep geological repository for radioactive waste and spent nuclear fuel must be submitted to the Government by 31 December 2030.

The final site for the DGR will subsequently be subjected to a detailed geological survey and the data obtained will be used to demonstrate the fulfilment of safety requirements and, thus, to demonstrate that the selected site is suitable for the location of the DGR.

Guarded area

A guarded area is an area in which category III nuclear material is located or a protected area.

HLW storage facility

The HLW storage facility is intended for the storage of SNF and solid RAW produced by ÚJV Řež, a.s. and Research Centre Řež. The construction of the storage facility took place in the period 1981–1988. Trial operation began in 1995, and the storage facility has been in permanent operation since 1997.

In-depth protection

In-depth protection is a protection method based on several independent levels that prevent the possibility of the exposure of workers and the population, the spread of ionising radiation and the leakage of radioactive substances into the environment.

Institutional inspection

Institutional inspection is a set of activities that ensure the maintenance and monitoring of radioactive waste repositories and the surrounding area following closure for a period specified in the respective documentation.

Isolation part of the repository

A rock environment with radioactive waste without the presence of category 3 water-bearing faults that could provide preferential pathways for the migration of radionuclides.

Long-term safety

The long-term safety of the repository refers to safety in the period following the closure of the repository up to the end of the defined lifetime of the repository.

Natura 2000

System of protected areas (bird areas, European-scale important sites) in European Union member states.

Nuclear facility

1) a building or operational unit, which includes a nuclear reactor that uses a fission chain reaction or other nuclear chain reaction,
2) spent nuclear fuel storage facility,
3) fresh nuclear fuel storage facility, if it is not part of another nuclear facility,
4) enrichment plant, nuclear fuel production plant or spent nuclear fuel reprocessing plant,
5) radioactive waste storage facility, with the exception of radioactive waste storage facilities that are part of another nuclear facility or other workplace where radiation activities are carried out,
6) radioactive waste repository, with the exception of repositories for waste containing exclusively natural radionuclides.

Nuclear facility site

The area for the siting of a nuclear facility that will be affected by the various phases of the life cycle of the facility.

Nuclear safety

Nuclear safety is the state and ability of a nuclear facility and the persons that operate the nuclear facility to prevent the uncontrolled development of a fission chain reaction or the leakage of radioactive substances or ionising radiation into the environment, and to limit the consequences of accidents.

Optimisation limit

The effective dose, which according to the principle of the optimisation of radiation protection (section 82 of Act No. 263/2016 Coll.), must not be exceeded. In the case of the deep geological repository, this dose is set at 0.25 mSv per year for a representative person.

Physical protection

Physical protection is a system of technical and organisational measures that prevent the occurrence of unauthorised activities concerning nuclear facilities or nuclear materials.

Protected area

A protected area is an area in which category II nuclear materials located.

Radiation accident

A radiation accident is an event that cannot be handled by the operator or workers during whose shift the accident occurs and which requires the introduction of urgent measures for the protection of the population.

Radiation emergency

A radiation emergency is an event that leads or may lead to the exceeding of radiation limits and which requires measures to prevent the exceeding of which or the worsening of the situation from the point of view of ensuring radiation protection.

Radiation protection

Radiation protection is a system of technical and organisational measures aimed at limiting the exposure of persons to and protecting the environment from the effects of ionising radiation.

Radioactive waste

A radioactive substance or device for which no further use is expected and which does not meet the conditions for its release from the workplace as set out in Act No. 263/2016 Coll.

Radioactive waste repository

A space, object or facility in which radioactive waste is disposed of.

Reference site

Reference site – a hypothetical site located in a suitable crystalline rock block in the Czech Republic and used for the assessment of the Czech disposal concept. It is assumed that the parameters of the reference site are average for the Bohemian Massif. For models that are tied to site-specific data, for example the terrain topology (e.g. geological, hydrogeological, etc. descriptive models), data from the site where the highest (and therefore least favourable) water flow rate is calculated is considered in the disposal layer of the model.

Representative person

An individual from the population that represents a modelled group of persons who will be most exposed to irradiation from a given source and via a given pathway.

Safety function

The safety function refers to the functions of systems, structures, components or other parts of a nuclear facility that are significant in terms of ensuring the nuclear safety of the facility.

Scenario

A sequence of events including, in particular, the random occurrence of an initiating event, the response of individual systems, structures and components that ensure safety and the transition of a nuclear facility to a safe or other state.

Spent nuclear fuel

Irradiated nuclear fuel that has been permanently removed from the core of a nuclear reactor and designated as waste by the originator. The term used fuel is used before it is declared as waste.

Storage of RAW/SNF

The storage of RAW/SNF is time-limited placement of radioactive waste or spent nuclear fuel in a space, object or facility with the intention of its reuse.

Technical safety

Technical safety is the state of the permanent compliance of selected equipment with the respective technical requirements in which there is no threat to human health, the environment or property.

Waste package

A waste package is a set of structural parts that serve to completely enclose radioactive content.

Explanation of selected geological terms

Brittle deformation

Fractures and faults found in rocks that were created during the formation of the rock itself, or during mechanical stress due to mainly endogenous forces. The properties of the rock itself, the degree of stress and its orientation, the ambient temperature and the rate of deformation all exert impacts on the formation of brittle deformations. The opposite of brittle deformation is ductile deformation, between which a wide range of ductile-brittle deformations are defined.

Crystalline

A complex of crystalline, mostly metamorphic and igneous rocks, mainly granitoids.

Ductile deformation

The "plastic" deformation of rocks in which no discontinuity surfaces are formed. The opposite is brittle deformation. A wide range of ductile-brittle deformations exist between these two extreme cases. Ductile deformation is dominant in the deeper parts of the earth's crust and in the mantle, where it is closely related to metamorphic conditions or the partial anatexis (partial melting) of rocks.

Excavation damaged zone, EDZ

A part of the rock mass in underground spaces adjacent to an excavated area (tunnel, cavern) that evinces significant, irreversible changes that lead to movements along existing fractures or the creation of new fractures. In high-stress environments, spalling of the rock blocks may occur.

Excavation disturbed zone, EdZ

A part of the rock mass in underground spaces adjacent to an excavated area (tunnel, cavern, mine gallery) that evinces insignificant hydromechanical and geochemical or reversible changes.

Fault

A fault is defined as a brittle failure along which occurred the observable displacement of the surrounding rocks in excess of 1 m.

Fracture

Brittle failure of a geological body (rock) via a change in the stress without observable displacement. Fractures comprise the most common type of failure of the mechanical cohesion of rocks and rock masses.

Glacial

Ice age - a period with a cold and dry climate. Glacials are divided into partial cooler fluctuations - stadials and warmer fluctuations - interstadials. The study of the history of the Earth suggests the occurrence of several ice ages; however, those that occurred over the last 1.8 million years have been studied most intensively. The temperature in the coldest glacial period in the Czech Republic was roughly 11–13°C lower than the current average (the average annual temperature over the last 50 years has ranged from 6.3 to 9.6°C). One glacial cycle lasts approximately 120,000 years (100,000 years - ice age and 20,000 years - interglacial).

Hydraulic gradient

The ratio of the difference in the level or pressure height of a liquid (water) and its flow pathway.

Hydrostatic pressure

Hydrostatic pressure is the pressure created in a liquid (usually water) by its own weight.

Lithostatic pressure

Pressure at depth caused by the weight of the overlying rocks. The pressure at the depth of the hypothetical repository, i.e. 500 m is approx. 13–15 MPa.

Stress state of the rock environment

Stress in a rock mass that is caused by the accumulation of energy. The causes comprise the weight of the overlying rocks, mountain-forming processes in the geological past and present, and other influences resulting from the geological structure of the rock mass (e.g. internal inhomogeneities, discontinuities, anisotropy of the rock properties, etc.).

Permafrost

The uppermost part of the lithosphere, which has a temperature of 0°C and lower for a period of two years or more. The thickness of permafrost ranges from a few centimetres to more than a thousand metres. In the polar regions, permafrost occurs in places of permanent ice and tundra regions. Permafrost may also occur below sea level – in this case it was formed during the last ice age, at the end of which it was flooded due to the rise in ocean levels; the temperature of the sea is currently not high enough to result in the melting of the permafrost.

Quaternary

A geological period covering roughly the last 2.6 million years. It is divided into the older Quaternary (Pleistocene) and the younger Quaternary (Holocene).

Saturation

The hydraulically uniform and continuous accumulation of gravitational groundwater in the rock, i.e. a continuous body of water (accumulation) in the collector through which hydraulic impulses may spread or mass transfer (transport) may occur.

Soil liquefaction

A phenomenon via which partially or fully saturated soil substantially loses its strength or stiffness due to an increase in pore pressure and the creation of significant deformation, whereupon the effective stress drops to zero and the soil behaves like a liquid. Soil liquefaction occurs during dynamic stress conditions (e.g. during seismic events).

Spalling

Local destruction of the rock mass, during which parts of the rock wall suddenly loosen and are ejected with a characteristic cracking sound.

Vertical movements of the earth's crust

Very slow movements of the blocks of the upper part of the Earth's crust, in which the blocks move differentially along faults in the vertical direction. Such movements may be positive (incline) or negative (decline). The rate of movement in the Bohemian Massif is generally < 0.5 mm/year, i.e. (< 50 m/100,000 years).

Abstrakt

Tento dokument popisuje současný stav výzkumu a vývoje (VaV) SÚRAO k roku 2024 a plán na dalších 5 let. Dokument navazuje a částečně nahrazuje předchozí plán VaV SÚRAO 2020-2030. Aktualizace předchozího plánu byla iniciována na základě zhodnocení nařízení Komise (EU) 2022/1214 označované jako „Taxonomie“. Zásadním požadavkem Taxonomie je zahájení provozu hlubinného úložiště do roku 2050.

Hlavním cílem VaV aktivit pro nadcházející období je Výběr finální a záložní lokality HÚ dále pak aktualizace technického řešení HÚ, bezpečnostní hodnocení ukládacího konceptu HÚ a periodické hodnocení ÚRAO Richard, Dukovany, Bratrství.

Plán VaV SÚRAO je rozdělen do částí tak, aby pokryl všechny aktivity SÚRAO. Většina aktivit je zaměřená na přípravu hlubinného úložiště, a to konkrétně na inventář, geologickou charakterizaci 4 vybraných lokalit, projektové řešení, výzkum a vývoj inženýrských bariér a hodnocení jak provozní, tak dlouhodobé bezpečnosti. S výzkumnými aktivitami SÚRAO jsou úzce spjaty také experimentální práce v PVP Bukov, které jsou nedílnou součástí plánu. Další část plánu je zaměřená na provozovaná úložiště Dukovany, Richard a Bratrství, kde jsou aktivity VaV zaměřeny převážně na doplňková měření pro bezpečnostní rozbory a zhodnocení nových trendů v ukládání RAO.

Klíčová slova

Hlubinné úložiště (HÚ), ÚRAO Richard, ÚRAO Dukovany, ÚRAO Bratrství, výzkum a vývoj, SÚRAO, PVP Bukov

Abstract

This document provides a description of the current state of research and development (R&D) of SÚRAO as of 2024 and the plan for the next 5 years. The document builds on, and partially replaces, the previous SÚRAO R&D Plan for 2020-2030. The update of the previous plan was initiated following the evaluation of the Commission Regulation (EU) 2022/1214 referred to as the "Taxonomy", a fundamental requirement of which concerns the start of operation of the Czech deep geological repository (DGR) by 2050. The main objectives of the R&D activities for the upcoming period comprise the selection of the final and backup DGR sites, the updating of the DGR technical design, safety assessment of the DGR disposal concept and periodic assessments of the Richard, Dukovany and Bratrství repositories. The SÚRAO R&D Plan is divided into several parts. Most of the R&D activities are concerned with the preparation of the DGR, namely the waste inventory, the geological characterisation of the 4 selected sites, the design, research and development of the engineered barriers and the assessment of both operational and long-term safety. The experimental work at the Bukov URF is closely linked to the research activities of SÚRAO and forms an integral part of the R&D plan. The plan also focuses on the Dukovany, Richard and Bratrství repositories, concerning which the R&D activities are mainly concerned with research for safety analysis purposes and the evaluation of the latest trends in the disposal of RAW.

Keywords

Deep geological repository (DGR), Richard repository, Dukovany repository, Bratrství repository, R&D, SÚRAO, Bukov URF

1 Purpose of the document

The purpose of this document is to describe the current state of research and development (R&D) of SÚRAO as of 2024 and the R&D plan for the next five years. The document follows on from and partly replaces the previous SÚRAO R&D plan (Vokál et al. 2020). The update of the previous plan was decided based on the conclusions of the Optimisation Study (Vondrovic et al. 2022, TZ601/2022), which evaluated the requirements of the technical criteria described in Commission Regulation (EU) 2022/1214, supplementing Annex No. 1 of Commission Delegated Regulation (EU) 2021/2139, specifically points 4.26, 4.27, 4.28, 4.29, 4.30 and 4.31 (https://eur-lex.europa.eu/eli/reg_del/2022/1214/oj, referred to as the "Taxonomy"). One of the fundamental conclusions of the Optimisation Study was:

"It contains fundamental implications in terms of the preparation of the deep geological repository and the operation of the Dukovany repository. In the case of the Dukovany repository, it is recommended that a strategic study on its development be compiled in connection with the preparation of new nuclear sources. In the case of the deep geological repository, the main condition concerns the commissioning thereof in 2050." (Vondrovic et al. 2022)

The R&D plan takes into account the Radioactive Waste and Spent Nuclear Fuel Management Concept (the Concept) in the Czech Republic as approved by Government Resolution No. 597 of 26 August 2019 and the requirements of the Atomic Act No. 263/2016 Coll., and its various implementing regulations and safety instructions. It further takes into account Council Directive 2011/70/Euratom of 19 July 2011, which established a Community framework for the responsible and safe management of spent nuclear fuel and radioactive waste. The Directive, in Article 12, point f), requires that the research, development and demonstration activities necessary to implement solutions for the management of spent nuclear fuel and radioactive waste are described in the national programmes via which Member States demonstrate compliance with this Directive. The implementation of research and development activities is also necessary according to Article No. 8 of this directive with concern to the acquisition, preservation and further development of the professional competence and skills of employees.

The introductory chapters of this document provide a general insight into the issue of radioactive waste management. Subsequently, the chapters are divided according to research areas so that the document comprehensively covers the issue of the development of the Czech deep geological repository, the operation of the Dukovany and Richard repositories and the eventual closure of the Bratrství repository. Each chapter, which describes one research area, describes the status of the research conducted to date, the detailed research plan for the next 5 years and an outlook for the future in the respective research area.

This plan will be updated every five years in accordance with new knowledge and experience gained via ongoing research and development work.

2 The current situation regarding the disposal of SNF and RAW in the Czech Republic

The current situation regarding the disposal of SNF and RAW in the Czech Republic is as follows:

1) After being removed from the reactors, SNF is stored for several years in pools located in the main NPP production units; it is subsequently moved to a dry storage facility where it is placed in transport-storage packages. The Dukovany NPP (EDU) has been in operation since 1995 and has a 600-tonne capacity intermediate storage facility, which was filled in March 2006. A second storage facility with a capacity of 1,340 tonnes has been in operation since December 2006. The storage facility at the Temelín NPP (ETE) has been in operation since September 2010 and has a capacity of 1,370 tonnes. The storage capacity for SNF from existing EDU blocks is sufficient for 60 years of operation, whereas concerning the operational ETE blocks, the storage capacity covers roughly 30 years of operation. Up to the time of the commissioning of the deep geological repository (DGR), SNF from the 2 nuclear power plants will be stored in transport-storage packages in the SNF storage facilities located at the respective power plants. Concerning the preparation of new nuclear sources (NNS), options for the future storage/disposal of RAW and SNF from these sources are currently being assessed. More highly enriched nuclear fuel from research reactors at ÚJV Řež, a.s. was sent in the past to the Russian Federation for reprocessing; the reprocessed waste will eventually be returned to the Czech Republic for disposal. It is expected that SNF from other research reactors and the high-level waste (HLW) from its reprocessing will be stored at facilities located at ÚJV Řež, a.s., or at Research Centre Řež s.r.o.,
2) during the operation and decommissioning of nuclear reactors and when dealing with ionising radiation sources, RAW is produced in the gaseous, liquid and solid forms. A minor part of such RAW is stored and released into the environment once its activity drops below official release levels. The largest group of radioactive waste by volume consists of low- and intermediate-level waste (LLW and ILW); the processing and treatment technologies for such waste are well established and are applied by the generators of RAW in the Czech Republic. Since the radioactivity of LLW decreases significantly within a few hundred years, it can be disposed of in near-surface repositories,
3) LLW from the nuclear power industry is disposed of in the Dukovany surface repository located within the Dukovany nuclear power plant complex. The total volume of the disposal spaces is sufficient for all the waste generated via the operation and eventual decommissioning of the currently operational Dukovany and Temelín power plants, provided the waste fulfils the conditions for acceptability for disposal, even in the case of the extension of the operation of these power plants to 60 years (and including 1 NNS),
4) LLW and certain types of ILW from the industry, research and healthcare sectors are disposed of at the Richard (near Litoměřice) and Bratrství (near Jáchymov) repositories; the Dukovany repository is also partly used for this purpose. The operation of all the country’s disposal facilities, including the monitoring of the already closed Hostim repository, is ensured by SÚRAO in accordance with the required permits

issued by the SÚJB and, in the case of old mine workings, in accordance with mining regulations,

5) waste contaminated with natural radionuclides arising from the operation of workplaces that use NORM (naturally occurring radioactive materials) is regarded as a specific category of waste. It is generated via the processing of certain non-uranium ores and phosphate raw materials, the transport and processing of crude oil and in the water industry. Provided such waste meets the conditions for disposal in the environment, it is disposed of in municipal or hazardous waste landfill sites. If the waste exceeds the legal content limit values, it is disposed of (in certain cases stored) together with LLW and ILW in RAW repositories.

Preparing for the construction of radioactive waste repositories is very long-term process and includes several phases (see Fig. 1), all of which require the acquisition of new knowledge, especially concerning the provision and continuous enhancement of nuclear safety and radiation protection.

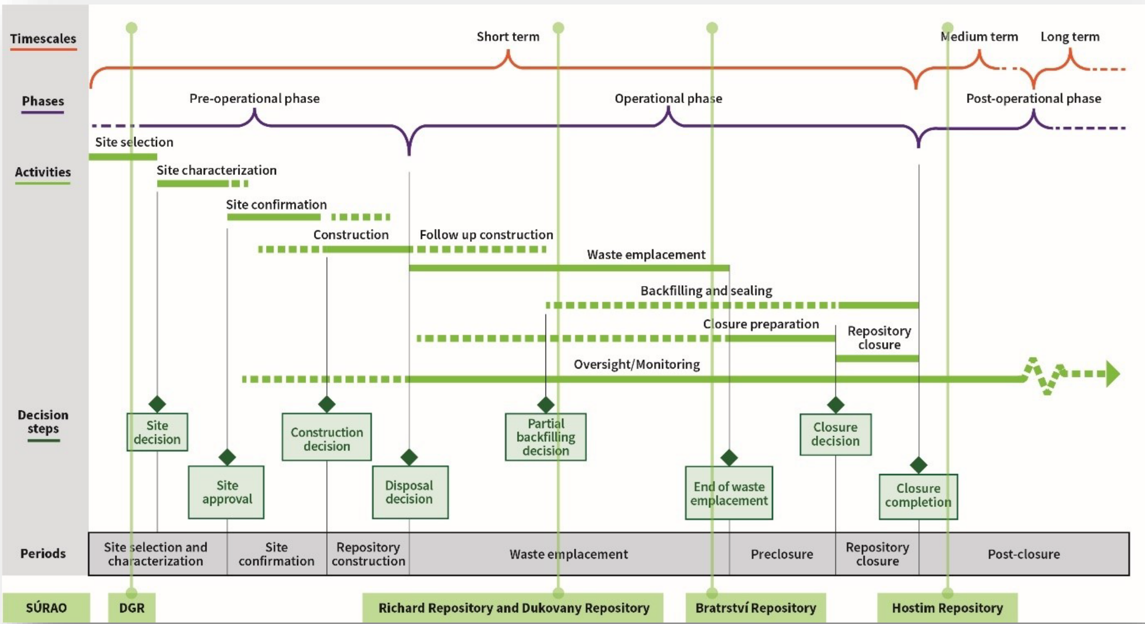

Fig. 1 Reference time frame (showing the main milestones) for the construction of a deep geological repository (ICRP, 2013 - modified) also showing the Czech RAW repositories

3 SÚRAO's approach to research & development

The preparation of the SÚRAO R&D plan was based on the following four approaches to fulfilling the various R&D objectives:

- research at the national level required for the conducting of projects,
- engineering solutions for the preparation of geological exploration work and the project design of, and preparations for, the construction of the deep geological repository,
- joint research at the bilateral and international levels using joint resources and knowledge, especially European framework R&D programmes and
- on the basis of contracts with countries with more advanced research programmes.

All these options are assessed during the preparation of research and development programmes aimed at meeting the objectives of the Concept (2019). It is clear that while it is possible to adopt the relevant methodologies from other countries, the use of the results of experiments conducted abroad is limited due primarily to differences in the geological characteristics of individual repository sites. In addition, the conducting of domestic research requires the formation of domestic research teams that will be needed for several decades into the future.

Joint research activities at the bilateral or international level; via the use of joint resources and knowledge, especially EURATOM European framework R&D programmes, it is often possible to obtain results significantly faster and cheaper than via purely domestic research. With concern to such cooperation, the key European programme concerns EURAD (Grant No. 847593, see Appendix 1), which involves the participation of more than 100 organisations. The EURAD programme covers several crucial areas related to the development of deep geological repositories (EURAD SRA 2023); this five-year programme will be concluded this year (2024). A similar European project, PREDIS, is focusing on activities/processes associated with radioactive waste prior to its disposal; this four-year project is also scheduled to end this year. These projects will be followed up by the EURAD2 programme that will commence in autumn 2024 and which will cover the activities involved in both the above-mentioned programme. SÚRAO is an active participant in the ongoing EURAD and PREDIS programmes and plans to participate in EURAD2.

SÚRAO also takes advantage of bilateral cooperation with countries that are more advanced than the Czech Republic in terms of DGR development, i.e. especially Finland and Sweden, whose repositories are also located in crystalline rocks. Cooperation with these countries is used by SÚRAO, e.g. in the development of the disposal concept, the design of the DGR itself and the evaluation of the materials to be used in the engineered barriers.

In terms of the selection process for the final site of the DGR, SÚRAO makes full use of bilateral cooperation with Switzerland, which selected the final location for its DGR in 2022.

Concerning the preparation of the construction and engineered components of the future DGR, the use of SÚRAO's own capacities is a necessary prerequisite for the preparation of the project design and for obtaining the key permits and licences for the future operation of the DGR.

A significant part of SÚRAO's research and development plan is related to the preparation of the Czech DGR. From the point of view of R&D, the requirements set by the DGR significantly exceed the normal requirements for the preparation of other nuclear facilities or repositories intended for the disposal of low-level waste due, primarily, to the currently considered maximum time frame for the DGR safety assessment, i.e. up to one million years following closure (Vrba et al. 2023). Even the time frame for the preparation of the DGR and its operation up to final closure significantly exceeds the usual time for the preparation and operation of other nuclear facilities. In contrast to the nuclear power plant siting process, which is usually based on a specific nuclear power plant project, the DGR project requires the simultaneous preparation of the DGR project itself and the DGR siting process. An equally important factor is that when attempting to prove the safety of the DGR, it is first necessary to understand the processes that may occur within the facility over an extremely long time period and which will potentially influence the behaviour of the various DGR components, i.e. the so-called multi-barrier system.

The various components of the DGR multibarrier system will both complement and influence each other and, as a whole, must meet all the legislative requirements set out for ensuring long-term safety in Act No. 263/2016 Coll., as amended, see Fig. 2.

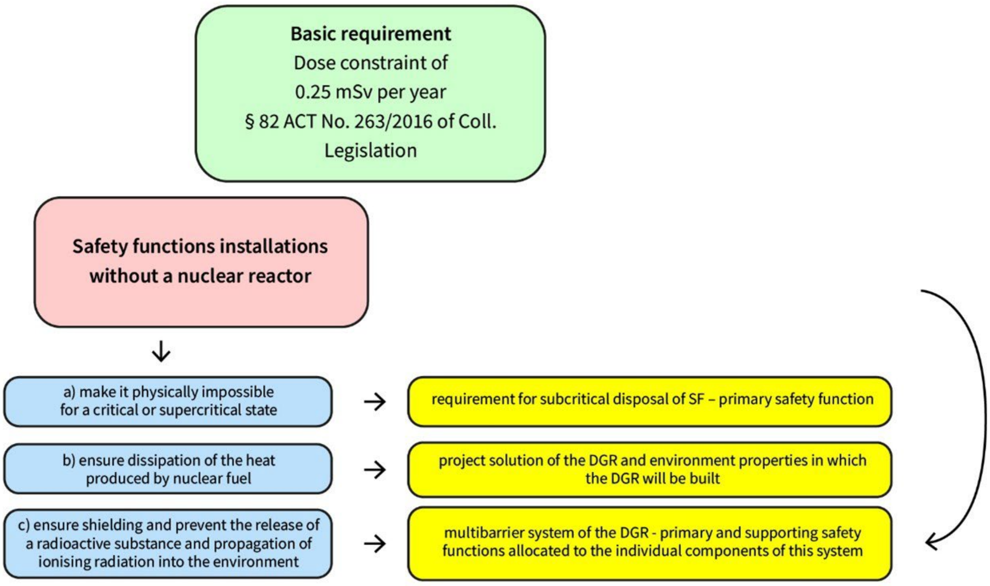

Fig. 2 Requirements for the DGR as set out in currently applicable legislation and the relationships between the various safety functions (Gondolli et al. 2018a)

The preparation of the R&D plan also takes into consideration the recommendations of the Implementing Geological Disposal for Radioactive Waste – Technology Platform (IGD-TP, 2020), as shown schematically in Fig. 3. It is also clear from the figure that the preparation of DGRs takes place both stage-by-stage and iteratively.

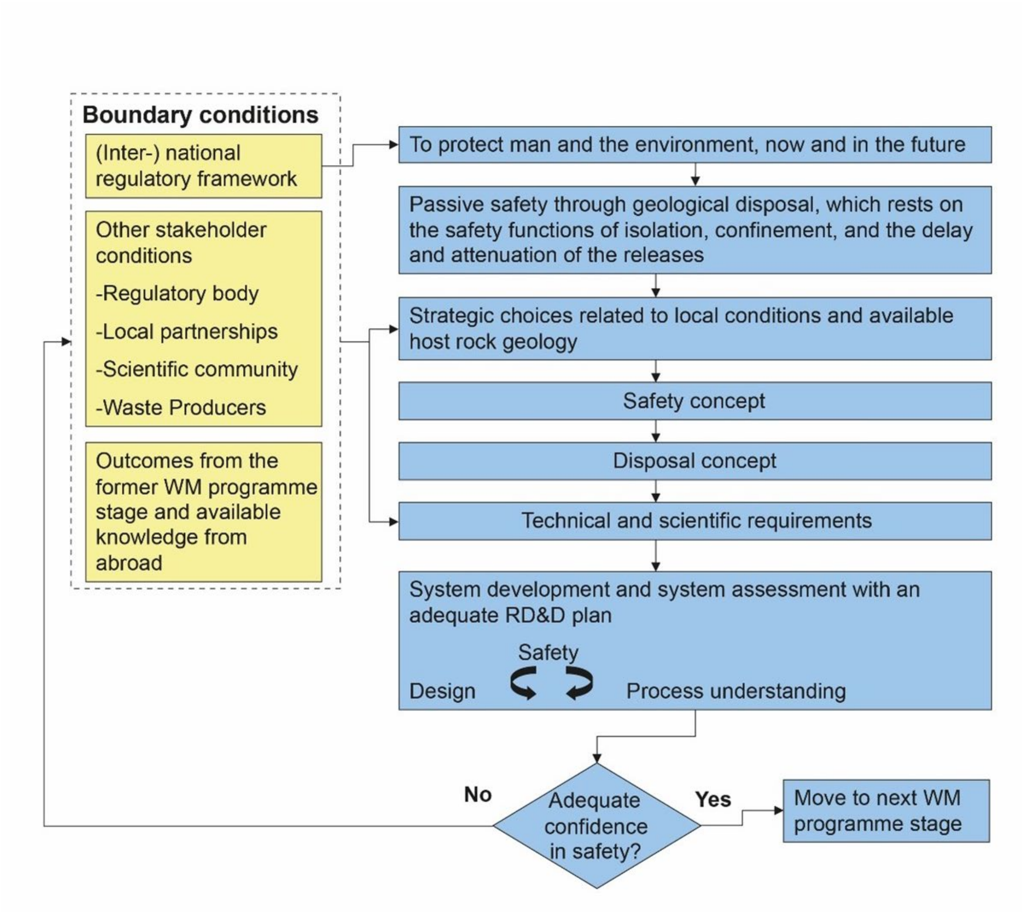

Fig. 3 Description of the various components of the R&D plan for the DGR according to IGD-TP – SRA, 2020 (modified)

SÚRAO's R&D plan is divided into two parts – research activities associated with the development of the DGR and R&D for the support of operational repositories.

Regarding the preparation of the DGR, R&D activities are divided into the following 10 areas:

1) Inventory and the properties of waste
2) Geological characterisation of candidate DGR sites
3) Project design of, and preparations for, the construction of the DGR
4) Evaluation of the impacts of the DGR on the environment
5) Waste disposal packages
6) (Back)filling of the disposal wells and tunnels
7) Other DGR components
8) Evaluation of DGR operational safety
9) Evaluation of DGR long-term safety
10) Research activities at the Bukov URF

The research activities related to the Dukovany, Richard and Bratrství operational repositories result primarily from SÚRAO's obligations to conduct regular deterministic, periodic and continuous safety assessments and special assessments in the event of changes in terms of the use of nuclear energy (Act No. 263/2016 Coll., section 48) that affect the repositories. The compilation of safety assessments assists in enhancing the level of nuclear safety to a reasonably feasible extent (Act No. 263/2016 Coll., section 49) from the point of view of the current level of science and technology (Act No. 263/2016 Coll., section 5), and to accurately evaluate those factors that are decisive in terms of assessing the acceptability of locations for the siting of nuclear facilities. Hence, it is necessary to continuously monitor the development of science and technology and to apply the findings to enhance nuclear safety. A further important factor in terms of R&D concerns the need to ensure sufficient capacity for the disposal of all the types of radioactive waste that will be generated in the Czech Republic. Research and development in this area can be divided into three areas:

1) Updating of the safety assessments of operational repositories,
2) Application of new research findings so as to enhance nuclear safety and radiation protection,
3) Ensuring sufficient repository capacity for the disposal of all the RAW generated in the Czech Republic.

The final chapter addresses issues concerning the disposal of NORM/TENORM waste, i.e. waste that contains only naturally occurring radionuclides so as to fulfil the objectives of the Concept (2019).

4 Research & development objectives

Concerning the upcoming period 2024-2028, the main aims of SÚRAO's research and development activities are summarised in the form of the four points listed below; the first three refer to preparations for the DGR and the fourth point to operational repositories.

1. Selection of the final and backup DGR sites up to 2030
2. Update of the DGR technical design
3. Safety assessment of the DGR disposal concept
4. Periodic safety assessments of operational repositories and related additional research

Aimed at fulfilling these aims, key activities, which are listed together with the respective time schedules were defined, see Tab. 1. The time estimates are purely indicative since most of the listed activities depend on the acquisition of data from the candidate DGR sites, which SÚRAO can obtain only after the declaration of exploration areas for special intervention into the earth's crust in accordance with section 22a of Act No. 62/1988 Coll. SÚRAO submitted applications for all 4 sites in February 2023; however, at the time of the writing of this report (April 2024) no decisions have yet been announced. More precise details of the outputs and deadlines will be announced during the preparation of public tenders and the selection of suppliers. The schedule will, therefore, be updated according to the development of the situation at the 4 sites.

The fulfilment of most of the key activities will require inputs from several projects. The various inputs are described in more detail in the respective sub-chapters of the Ongoing and planned projects section for each expert area (see Tab. 10 to Tab. 18, Tab. 21 and Tab. 22).

Tab. 1 SURAO's key R&D activities 2024–2028, classified by expected year of completion – indicative schedule

No.	SÚRAO key activity 2024–2028	from	to
1.	Update of the SNF inventory	2022	2024
2.	Update of the DGR life cycle schedule in connection with the acceptance of Taxonomy conditions	2023	2024
3.	Study of the economic and socio-demographic benefits and risks of the construction of the DGR	2022	2025
4.	Final decision on the siting of the surface areas at the selected DGR sites	2023	2025
5.	Performance assessment of the proposed DGR barriers	2021	2026
6.	Verification and validation of mathematical and computational models for DGR safety analyses	2021	2026
7.	Periodic safety assessments of the Richard, Dukovany and Bratrství repositories	2022	2026
8.	Evaluation of the long-term safety of the Czech SNF disposal concept at the reference site	2023	2026
9.	Geological research at the sites	2024	2026
10.	Updating of the technical design of the buffer, backfill and disposal chamber fillings for ILW	2026	2026
11.	Updating of the DGR technical design	2024	2027

No.	SÚRAO key activity 2024–2028	from	to
12.	Descriptive models of the selected sites	2027	2028
13.	Assessment of the impact of the DGR on the environment and population (DGR EIA study), background studies for the selected sites	2027	2029
14.	Siting studies at the selected locations	2027	2029
16.	Initial safety analysis reports for the selected sites	2025	2029
17.	Selection of the final and backup sites	2029	2030

4.1 Basis for the selection of the final and backup DGR sites

The selection of the final and backup sites is planned for the period 2028–2030, by which time all the necessary documents will have been collected on which to base the selection. The selection process for the final and backup sites can be divided into 4 stages (see Fig. 4), which are described in more detail in the following chapters. One of the key conditions for the initiation of most of the related research activities concerns the declaration of exploration areas for special intervention into the earth's crust according to section 22a of Act No. 62/1988 Coll. SÚRAO submitted applications for all 4 sites in February 2023 and estimated that the process would be completed by the beginning of 2024; however, at the time of the compilation of this report (April 2024) no such decisions have been announced.

Government Resolution No. 1350 of 21 December 2020 on the Radioactive Waste Repository Authority's Activity Plan for 2021, the Three-Year Plan and the Long-Term Plan and on the Concept for the preparation of a Deep Geological Repository for Radioactive Waste and Spent Nuclear Fuel in the Czech Republic, instructed the Deputy Prime Minister, the Minister of Industry and Trade and the Minister of Transport to submit to the Government by 31 December 2030 a proposal for a final site and a proposal for a backup site for the future deep geological repository for radioactive waste and spent nuclear fuel.

The final site will subsequently be subjected to a detailed geological survey and the data obtained will be used to demonstrate the fulfilment of safety requirements and, thus, to demonstrate that the selected site is suitable for the location of the DGR. One backup site will be held in reserve in the case of the occurrence of unforeseen events concerning the detailed characterisation of the final site. The backup site is an alternative site that could be used in the event that it is not possible to locate the DGR at the selected final site for technical, safety, capacity or other reasons.

Fig. 4 Selection of the final and backup DGR sites divided into stages

4.1.1 1st Stage – collection of data and other inputs (2024-2027)

This stage will include the collection of the necessary data that will be used to describe and assess the sites. The data and other necessary information will be provided by the results of a number of projects, some of which are already underway, and others are in the tender documentation preparation stage.

1. Update of the technical design of the DGR

This concerns the updating of the DGR technical design with new research findings. The supporting document in this case comprises a report by Hausmannová et al. (2023) and outputs from planned projects. It will involve primarily the updating of various components of the DGR based on new knowledge, e.g. in the fields of DGR thermal dimensioning, engineered barriers and the dimensions of the transverse profiles of the underground corridors.

2. Safety assessment of the Czech disposal concept - reference site

A safety assessment of the proposed Czech disposal concept will be carried out for the reference site. The assessment will include the conducting of sensitivity analyses and the evaluation of uncertainties, the results of which will be considered in the safety analysis in accordance with section 9, paragraph 3, c) of decree No. 377/2016 Coll. Further information is provided in chapter 5.11.2.6.

3. Socio-economic study

The aim is to evaluate the economic and socio-demographic benefits and risks of the DGR in terms of the development of the wider regions of the selected sites in the various phases of the DGR life cycle. Such studies are currently being compiled for each of the four sites and are expected to be completed in May 2024. The reports will subsequently be updated following the determination of the exact locations of the surface areas at the sites, including their connection to the local transport infrastructure. These studies will be merely supportive, they will not influence the site selection process.

4. Data from the sites – geology

Various types of geological research are planned at the 4 sites, e.g. mapping, monitoring, drilling with subsequent borehole testing, the study of drill cores, excavation work and geophysical measurements. The fundamental legislative requirement in terms of starting the exploration work concerns the declaration of exploration areas for special intervention into the earth's crust in accordance with section 22a of Act No. 62/1988 Coll. Further information on the geological research planned at the sites is provided in chapter 5.4.2.

5. Data from the sites – environment

This part involves the collection of background information for studies on the impact of the DGR on the environment (e.g. noise, impact on the landscape, etc.) and the initiation of the collection of other necessary data and the establishment of a long-term monitoring system. At present, bio-screening data is available for each of the 4 sites, summaries of which are provided in the respective SÚRAO reports (Šikulová et al. 2023 a-d). Further information on the research planned at the sites is provided in chapter 5.6.2.

4.1.2 2nd Stage – data processing (2027-2028)

Based on the data collected in Stage 1, **descriptive site models** (Valter et al. 2023) will be created in which the information on the sites will be synthesised. Subsequently, a **preliminary assessment of the long-term safety of the selected sites** will be conducted (see chapter 5.11.2.7) based on the descriptive site models and using the results of the safety assessment of the Czech disposal concept at the reference site (see chapter 5.11.2.6). The result of this assessment will comprise an indication of whether the given site is compatible with the proposed technical design of the DGR from the safety point of view.

4.1.3 3rd Stage – background studies (2028-2029)

The outputs of the previous stages will serve as input for the creation of background studies for the final stage, i.e. the selection of the final and backup DGR sites:

1. Siting studies

Siting studies will serve to verify the locations of the underground and surface areas of the DGR for SNF and the disposal of radioactive waste that is unacceptable for disposal at existing near-surface repositories via the results of the surveys of the sites. The verification of the location of the underground area will include the assessment of the dimensions of the potentially usable rock blocks according to the expected SNF and RAW inventories and the determination of the volume of excavated material for the proposed technical design. The study will also define the optimal location of the surface area, including its connection to the local infrastructure and the approach to the construction of the so-called hot chamber. The study will further include the assessment of conflicts of interest, and the identification and evaluation of the uncertainties inherent in the site suitability proposal.

2. Initial safety analysis reports

The Initial safety analysis report will serve to summarise the assessment of the site from the point of view of the potential for the siting of the DGR. The format of the report will be in accordance with the requirements of section 20 of Decree No. 378/2016 Coll. on the siting of nuclear installations. The study assesses all the available knowledge on the characteristics of the assessed site and their influence on nuclear safety, radiation protection, technical safety, monitoring of the radiation situation, emergency management and security during the life cycle of the nuclear facility. In particular, the report considers those characteristics of the site for the location of the nuclear facility that rule out the siting of a nuclear facility.

3. Assessments of the impact of the DGR on the environment

The aim of this study is to assess the impacts of the construction of the DGR at a given site on the various components of the environment (soil, water, air, the character of the landscape, fauna, flora, ecosystems, climate), public health, natural resources, cultural monuments, etc. The study will be compiled in accordance with Annex. No. 4 of Act No. 100/2001 Coll. (parts: B, C, D, E) using the outputs of planned studies (see 5.6.2) and assessments. The main subject of the assessment will comprise the DGR surface area and/or components thereof and its connection to the existing transport infrastructure.

4.1.4 4th Stage – selection of the final and backup sites (2029-2030)

The final stage of the process will concern the selection of the final and backup DGR sites. SÚRAO is currently preparing an evaluation methodology that will be based on several assessment levels. Those sites that meet the requirements for the siting of a nuclear facility and where it is deemed possible to preliminarily assess long-term safety will be included in the final selection process.

4.2 Updating of the technical design of the DGR

The technical design of the DGR for radioactive waste in the Czech Republic has been under development since the 1990s (Holub I., et al., 1999). The input information on the rock mass and the waste inventory has been refined gradually over the years and new scientific knowledge in this area has been closely monitored. The current DGR technical design has been described in detail in the respective SÚRAO report (Hausmannová et al. 2023) on the whole of the DGR disposal system focusing particularly on the DGR underground complex, i.e. the underground workings, the engineered barriers and other components based on the currently assumed waste inventory, the rock environment, construction technology and disposal area configuration.

Concerning follow-up research work (site selection and future obligations, e.g. the securing of permits for the siting of nuclear facilities), the technical design will need to be updated and supplemented with additional relevant information. This will concern, for example, the optimisation of the dimensions of both the underground and the surface complexes of the DGR, the more detailed description of the waste transfer node, and the detailed technical design of the ILW disposal area.

4.3 Periodic assessment of the safety of repositories and additional research

Concerning operational repositories, the main objective relates to the compilation of periodic safety assessments, which is required by legislation once every 10 years (section 15 paragraph 2 of Act No. 162/2017 Coll.). A detailed assessment is being planned for 2026 aimed at fulfilling this requirement. The assessment will further include the analysis of available data and the identification of data that will need to be supplemented. This will allow for the design of the experimental programme and the updating of the surveillance programme.

The RAW disposal concept in the Czech Republic is well established, is fully in line with European practice and legislation and has been verified by the safe operation of RAW repositories over several decades. However, Czech atomic legislation still requires the monitoring of new trends and technologies, based on which several research areas have been identified that SÚRAO will focus on in the subsequent stage (see chapter 6).

5 Preparation of the deep geological repository

SÚRAO is currently preparing a project for the deep geological disposal of SNF and other RAW that does not meet the conditions for acceptability at existing operational repositories (Richard, Bratrství, Dukovany).

The preparation of DGRs is divided into several phases (see Fig. 5) according to the Specific Safety Guide SSG-14 international regulation (IAEA 2011b). Generally, it is divided into the pre-operational and operational stages and the stage following the closure of the DGR. According to the currently valid DGR preparation schedule (Vozár et al. 2023), the preparation phase is planned for the period up to 2050 at which time the DGR is scheduled to be put into operation. The operational phase is currently expected to continue until 2167, followed by approximately 300 years of the institutional inspection of the repository.

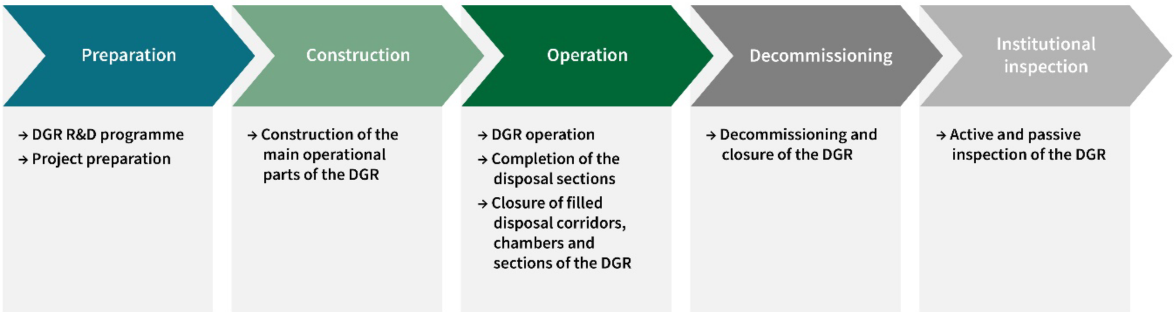

Fig. 5 Diagram of the DGR life cycle

The **DGR preparation phase** commenced in the Czech Republic in around 1990 and includes the selection of the final and backup DGR sites and their detailed characterisation to the depth of the future disposal horizon.

The main aims of the preparation phase are:

- to obtain information, documentation and data on the basis of which it will be possible to select the final and backup sites for the DGR,
- to define and process the necessary technical, technological and project documentation aimed at securing the permits required by legislation in the various stages of development and other documentation including safety assessment documentation,
- based on the processed project documentation, to obtain the permits required for defined structures, including in the DGR surface area,
- to initiate and implement construction preparations (preparation of the DGR area itself, connection of the DGR area to the technical and transport infrastructure) and
- to construct a characterisation (testing) laboratory at the depth of the future disposal horizon.

The **DGR construction phase** will begin following the confirmation of the suitability of the finally chosen site and after obtaining the permits necessary to commence construction.

The main aims of the construction phase will be:

- to construct the main operations-related buildings,
- to construct the underground area of the DGR and the technical infrastructure on the surface - the non-nuclear section,
- to construct the surface area of the DGR, the non-nuclear section of the 1st stage and buildings related to the mining work required for the DGR,
- to construct the nuclear facility area,
- to construct the DGR surface area, non-nuclear part, 2nd stage,
- to obtain permission for the immediate use of buildings and
- to obtain decisions on trial operation and final post-construction approval.

The **DGR operation phase** will begin once approval has been obtained for trial operation, based on which the post-construction approval decision will subsequently be issued.

The main aims of the operation phase will be:

- to accept and dispose of WDPs with SNF,
- to accept and dispose of WPs with RAW,
- to fill and stabilise the disposal wells with WDPs
- to backfill the chambers with WPs and the disposal corridors,
- to continue the construction of the underground complex, i.e. new disposal sections during operation, nuclear, non-nuclear parts,
- to prepare documentation for nuclear facility decommissioning and
- to gradually close the DGR.

The **DGR decommissioning phase** will begin following the disposal of all SNF and approval has been obtained for decommissioning the nuclear facility.

The main aims of the decommissioning phase will be:

- to decommission parts of the nuclear equipment (transfer node, hot chamber) and related items,
- to manage the RAW generated during the decommissioning of nuclear equipment,
- to dispose of WPs with RAW,
- to backfill and close the chambers with disposed of WPs with RAW and
- to close the DGR (backfilling and closure of other DGR mined areas and access corridors).

The **DGR institutional inspection phase** will begin following the complete closure of the DGR.

The main aims of the institutional inspection phase will be:

- period of active institutional inspection – to maintain, monitor and ensure the surveillance of the DGR and the surrounding area,
- period of passive institutional inspection – to preserve information on the DGR and its existence at the site and
- retain all the other information as required by Act No. 263/2016 Coll.

5.1 DGR management system

The implementation of the preparation phase and the subsequent phases will require an individual project-based system approach to managing the various processes and requirements and the data obtained. Furthermore, one of the main priorities will be the preservation of information, data and knowledge throughout the life cycle of the DGR.

5.1.1 Management system for the siting of the DGR nuclear facility

The management system for the siting of the DGR nuclear facility will be performed via the compilation of separate management documentation by SÚRAO in accordance with the provisions of Act No. 263/2016 Coll. and decree No. 408/2016 Coll. on management system requirements, and decree No. 378/2016 Coll. on the siting of nuclear facilities, which sets out the activities that must be ensured by SÚRAO in accordance with section 113 paragraph 4) of Act No. 263/2016 Coll., with respect to the siting of nuclear facilities – the DGR - in the Czech Republic. The documentation will form part of that required for authorised activities concerning the siting of nuclear facilities in accordance with section 9, paragraph (1), letter a), Act No. 263/2016 Coll.

The authorised activity in this case concerns SÚRAO's aim of siting the DGR nuclear facility via the selection of final and backup sites:

Assessment of the characteristics of the area for the siting of the nuclear facility. Assessment in terms of the potential for the characteristics to influence nuclear safety, radiation protection, technical safety, radiation situation monitoring, radiation emergency management and security during the life cycle of the nuclear facility. (According to sections 3 - 17 of Decree No. 378/2016 Coll.)

Assessment of the characteristics of the area for the siting of the nuclear facility according to special requirements. Assessment of whether, from the point of view of the insulation and containment properties of the rock environment in combination with artificially created barriers, the characteristics ensure that the disposed of RAW will not cause higher exposure to a representative person during the expected development of the DGR than the set dose optimisation limit. (According to section 18 of Decree No. 378/2016 Coll.)

Processing of the documentation for the siting of the nuclear facility. The compilation and processing of the initial safety report and other documentation and records related to the activities involved in the siting of the DGR. (according to section 20 of Decree No. 378/2016 Coll.)

The management system programme for the siting of the nuclear facility (DGR) must be regularly updated in accordance both with the development of the DGR itself and the updating of legislative regulations (Decree No. 408/2016 Coll., on management system requirements). SÚRAO will apply the basic principles of project management when updating the process management system.

5.1.2 Requirements management system for the selection of the final and backup DGR sites

A number of previous SÚRAO documents have addressed requirements for the selection of a site for the DGR nuclear facility. Concerning site selection, the respective documentation was summarised in 2014 in document MP.22. In 2017, the 2nd edition of the MP.22 document was compiled so as to include the requirements of the new Atomic Act and the implementing decrees thereof (Vokál et al. 2017).

The requirements management system for site selection will be modified for the requirements of the final and backup site selection process. The document fully respects the requirements of the legislation set out in the Atomic Act and the implementing decrees thereof, especially decree No. 378/2016 Coll. on the siting of nuclear facilities and the requirements set out by SÚRAO's supervisory authorities, e.g. the Ministry of Industry and Trade, the SÚJB and the Ministry of the Environment.

5.2 DGR safety concept

The SÚRAO DGR safety concept is based on the principle of optimising radiation protection and the application of best practice (the best available technology and materials) so as to ensure radiation protection with due regard to the costs involved and the amount of the effective collective dose. The text below focuses on the safety concept for SNF disposal only. The safety concept for the disposal of other radioactive waste in the DGR is under preparation.

The safety concept that was drawn up in 1999 (Holub et al. 1999) was based on the Swedish KBS-3 disposal concept (SKBF/KBS 1983), which relied on the thermodynamic stability of WDPs with outer covers made from copper, which corrodes very slowly in the reducing environment of crystalline rocks at depths of several hundred metres below the surface and surrounded by compacted bentonite. Subsequently, due to the lower content of chlorides in the groundwater of the crystalline rocks in the Czech Republic than in Sweden and Finland, and technical and material availability and price considerations, the copper WDP concept was replaced by a steel double-walled WDP concept with an inner casing made of stainless steel and an outer cover made of carbon steel.

The current SÚRAO safety concept for the preparation of the DGR is described below:

1) The containment of RAW for as long as possible in two-layer, steel WDPs (Matulová et al. 2023), which physically prevent the occurrence of critical conditions during both the operation and following the closure of the DGR and prevent the release of radionuclides for the required time with concern to the properties of the waste and the events and processes that may occur. The proposed WDP concept must provide for the retention of radionuclides for hundreds of thousands of years in environments without the occurrence of significant microbial activity and without the presence of higher concentrations of corrosion-supporting substances. These conditions can be influenced via the use of suitable filling materials that prevent the proliferation of corrosion-accelerating bacteria and limit the flow of water around the WDP and the rapid transport of corrosion-promoting substances to the WDP.

2) The retardation, following the breaching of a WDP, of the migration of radionuclides within the filling material surrounding the WDP. The filling system (compacted bentonite) will primarily act to prevent the migration of radionuclides in the form of colloids, which are able to rapidly penetrate into the rock environment, and to retard the migration of radionuclides due to the fact that migration can only take place via diffusion. The rate of migration of most radionuclides will also be retarded via sorption.
3) The determination of a suitable site with a suitable rock environment:
    a) the fulfilment of the safety functions of the engineered barriers in particular via a stable, reducing environment without the presence of oxygen that provides favourable conditions for the slow degradation of the engineered barriers, the low solubility of the uranium matrix in the SNF and the low solubility of radionuclides,
    b) the very low probability of seismic-tectonic events at a depth of several hundred metres below the earth's surface, which could lead to the premature mechanical damage to WDPs,
    c) the low probability of human contact with RAW due to the fact that the repository is located several hundred metres below the surface of the earth and that there are no known resources (e.g. mineral resources, geothermal energy, etc.),
    d) the very slow migration of radionuclides into the environment due to low water flow velocity, low fracture density and sufficient distance from geological structures with high water flow velocity rates.
4. To ensure the sufficient isolation of the waste against climatic events on the surface (erosion and permafrost) via the siting of the DGR disposal section at a sufficient depth below the surface.

The current safety concept is based on a number of assumptions that need to be verified going forward via the research and development work described herein. The assessment of this concept will be performed as part of the long-term DGR safety assessment: more information is provided in chapter 5.11.2.

5.3 Inventory and properties of radioactive waste

The disposal areas of the DGR will be divided into two parts (Hausmannová et al. 2023). One part is intended for the disposal of SNF and HLW, e.g. vitrified (reprocessed fuel from the LVR-15 reactor) waste and fuel assemblies with lower enrichment levels (< 20%) from the LVR-15 reactor. The second part will serve for the disposal of ILW (Podlaha et al. 2023a, 2023b).

The Czech Republic currently has two nuclear power plants in operation, i.e. the Dukovany and Temelín NPPs. The design lifespan of the Dukovany NPP is 30 years and the Temelín NPP 40 years. However, the operator has implemented a programme for the long-term operation of both plants beyond their projected lifespans, i.e. up to at least 60 years. When preparing the DGR, it is also necessary to take into account potential new nuclear sources (NNS) also with a minimum lifespan of 60 years, as stated in the Concept (2019). The construction of 4 new units and small modular reactors is currently being considered. Thus, it will be necessary to closely monitor the situation concerning potential changes in the use of nuclear energy. The inventory presented in this report is based on the assumptions set out in the Concept (2019), i.e. the inventory includes 3 new nuclear units, but does not include small modular reactors.

An overview of the basic parameters for SNF based on the Concept (2019) is provided in Tab. 2. In the event of a decision to redesign and/or revise the number and type of new reactors, it will be necessary to significantly modify this part of the R&D plan. Concerning all the units (including NNS), the cooling time for the fuel assemblies, i.e. the time between the removal of the fuel from the reactors and DGR disposal is considered to be 65 years. The existing nuclear units have a maximum burn-up of 60 MWd/kg, whereas fuel with a maximum burn-up of 70 MWd/kg is currently assumed for NNS. Based on these assumptions, the total number of WDPs will amount to 7,600. Tab. 3 shows the total mass of uranium, the mass of uranium in one WDP and the average heat output of one WDP for the individual power plants.

Tab. 2 Overview of basic SNF parameters based on the Concept (2019)

Parameter	**Unit**	**Type of nuclear reactor**		
		VVER-440	**VVER-1000**	**NNS**
Nuclear power plant	-	EDU	ETE	Not yet known
No. of units (nuclear reactors)	-	4	2	3
Max. nuclear fuel burn-up	$MWd \times kg_{TK}^{-1}$	60		70
Max. nuclear reactor operational time	year	60		
Min. time from the removal of the fuel from the reactor core to DGR disposal	year	65		
No. of fuel assemblies during the operational period	-	21,700	5,400	8,100
Mass of uranium in the SNF during the operation of all units	tonne	2,650	2,555	3,831

Tab. 3 Expected parameters and nos. of WDPs (Kobylka, 2019)

Parameter	**Unit**	**Type of nuclear reactor**		
		VVER-440	**VVER-1000**	**NNS**
No. of fuel assemblies in 1 WDP	-	7	3	
Mass of SNF in 1 WDP	kg	855	1,419	
Thermal output of 1 WDP 65 years from the removal from the active zone of the nuclear reactor	W	655	1,125	1,221
Total nos. of WDPs of the given type during the operation of all units	-	3,100	1,800	2,700

The SNF section will also serve for the disposal of vitrified RAW resulting from the reprocessing of highly enriched spent fuel and non-reprocessed low-enriched SNF (enrichment of lower than 20%) resulting from the operation of the LVR-15 research reactor. The vitrified HLW will be returned from the Russian Federation in two planned batches of 740 kg and 720 kg. Concerning the low-enriched fuel, a total of 250 fuel assemblies will have been used by the planned end of operation of the LVR-15 reactor in 2028. However, it is likely that the operator will extend the operation of the reactor until 2038, in which case, the total SNF output will amount to around 390 fuel assemblies.

Other waste (ILW) will be disposed of in the second part of the DGR (ILW section). It will comprise RAW originating from the decommissioning of nuclear facilities, RAW that does not meet the limits and conditions of acceptability for disposal in existing operational repositories and institutional RAW from the industrial, medical and research sectors. This part of the DGR will be located at such a distance from the SNF/HLW part that ensures no mutual interaction between these types of waste or that potential interaction will exert no significant impact on the DGR safety functions; this must be confirmed by the conducting of a detailed analysis.

The decommissioning of nuclear facilities is performed according to the design documentation of the respective facility and according to activation calculations supplemented by qualified estimates. Activation calculations have been performed for two options: immediate decommissioning – decommissioning commences following the end of operation of the facility, and gradual decommissioning – decommissioning commences 40 years after the end of operation (Podlaha et al. 2023a). The figures presented in this report refer to the gradual decommissioning variant (see Tab. 6 to Tab. 9), concerning which there will be a reduction in the activity of the waste from ETE, which will allow for the disposal of the RAW in a smaller number of WDPs (Podlaha et al. 2023a).

5.3.1 Work performed

Spent nuclear fuel

The SNF inventory was addressed in the Research support for the safety assessment of the deep repository project - SNF database sub-section (Rataj et al. 2015b). The SNF inventory is currently being updated and the selection (justification) of key radionuclides is being updated as part of the Updating of the inventory and properties of RAW for the DGR project, which will be concluded in September 2024 (SO2022-008, Annex 1). The SCALE calculation package, version 6.1.3, was used to calculate the composition of the SNF (Rataj et al. 2015a). Calculations were performed using the TRITON management module applying the NEWT 2D transport code. The SNF database lists the activities and masses of long-lived radionuclides. A list of the key radionuclides that are important from the point of view of long-term and operational safety is provided in Tab. 4. The calculation method, including the considered assumptions, is described in the final report by Rataj et al. (2015b).

Tab. 4 Key radionuclides important from the point of view of DGR safety (Rataj et al. 2015b).

Activation products	**Actinides**					**Fission products**
^{3}H						^{79}Se
^{10}Be	^{229}Th	^{230}Th	^{232}Th			^{85}Kr
^{14}C	^{231}Pa					^{90}Sr
^{36}Cl	^{233}U	^{234}U	^{235}U	^{236}U	^{238}U	^{93}Zr
^{41}Ca	^{237}Np					^{99}Tc
^{59}Ni	^{238}Pu	^{239}Pu	^{240}Pu	^{242}Pu		^{107}Pd
^{63}Ni	^{241}Am	^{242}Am	^{243}Am			^{126}Sn
^{93}Zr	^{244}Cm	^{245}Cm	^{246}Cm			^{129}I
^{93}Mo						^{135}Cs
^{94}Nb						^{137}Cs
^{108m}Ag					^{226}Ra*	^{151}Sm
^{166m}Ho						

** ^{226}Ra does not belong to the actinides group; it is formed as a subsidiary product during the decay of actinides*

The calculations included the determination of the residual heat output for one WDP filled with SNF. The residual power was calculated for the following fuel types:

- VVER-440 Gd-2M+ with an average enrichment of 4.38% and a burn-up of 60 MWd/kg_{MASS}
- VVER-1000 TVSAT with an average enrichment of 4.60% and a burn-up of 60 MWd/kg_{MASS}
- NNS with an average enrichment of 4.50% and a burn-up of 70 MWd/kg_{MASS}

The calculated residual power values were based on the models described in detail in a report by Rataj et al. (2015b), see Tab. 5. The residual power for one WDP is presented graphically in Fig. 6.

Tab. 5 Residual power at the point of the maximum value with concern to the WDP (centre of the WDP) for all 3 NPP types (Rataj et al. 2015b),

Time from removal [years]	VVER-440	VVER-1000	NNS
	Power [W/WDP]		
65	$8.65.10^{+2}$	$1.22.10^{+3}$	$1.55.10^{+3}$
115	$5.10.10^{+2}$	$7.12.10^{+2}$	$8.83.10^{+2}$
165	$3.70.10^{+2}$	$5.13.10^{+2}$	$6.26.10^{+2}$
215	$3.00.10^{+2}$	$4.16.10^{+2}$	$5.00.10^{+2}$
265	$2.58.10^{+2}$	$3.58.10^{+2}$	$4.25.10^{+2}$
465	$1.73.10^{+2}$	$2.42.10^{+2}$	$2.79.10^{+2}$
665	$1.31.10^{+2}$	$1.84.10^{+2}$	$2.10.10^{+2}$
865	$1.04.10^{+2}$	$1.46.10^{+2}$	$1.67.10^{+2}$
1065	$8.53.10^{+1}$	$1.19.10^{+2}$	$1.37.10^{+2}$

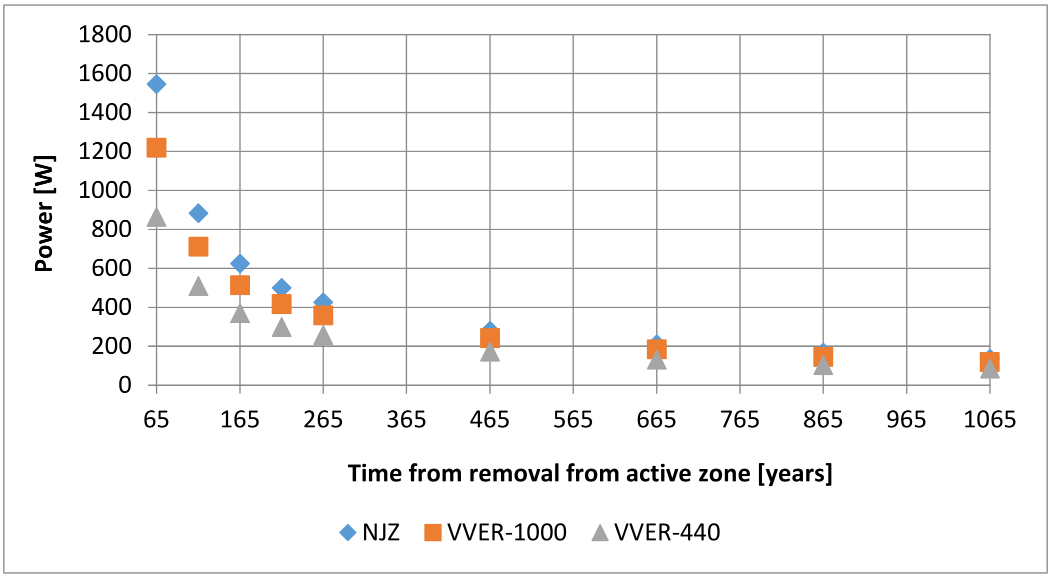

Fig. 6 Residual power at the point of maximum value with concern to the WDP for VVER-440, VVER-1000 and NNS (Rataj et al. 2015b)

ILW intended for disposal in the DGR

Based on the analyses prepared in reports by Podlaha (2023a, 2023b) and Čubová et al. (2017), it is assumed that the following types of radioactive waste materials will be disposed of in the DGR:

- carbon steel (inner walls of the ETE reactor shaft, structural parts of the ETE and EDU reactors),
- stainless steel (ETE and EDU reactor vessels including ETE and EDU reactor linings and reactor internal components),
- Al materials (absorption rods – B_4C + Al alloy; active zone basket, horizontal channels and thermal columns – $AlMg_5$ aluminium alloy; LVR-15 research reactor),
- BeO alloy (beryllium reflectors; research reactor LVR-15),
- concrete (reactor shaft),
- heavy concrete,

- serpentinite concrete (backfill),
- vitrified – sodium-aluminium phosphate glass (reprocessed fuel from the LVR-15 research reactor),
- solidified liquids or sludge in cement,
- sources of ionising radiation in sealed steel cases, and in metallic or crystalline form, level meters, therapeutic irradiators, industrial irradiators),
- ionisation fire detectors (metal plates with vaporised radionuclides, mainly ^{241}Am, in double-walled WPs).

The key radionuclides that could most seriously impact the safety of the DGR have been identified with concern to the above-mentioned waste (Podlaha et al. 2023a, 2023b; Čubová et al. 2017); the selection criteria comprised the mobility of radionuclides, their half-life, significant impacts on radiation protection in the operational phase of the DGR and long-term negative impacts on the human organism and the environment. The key radionuclides include: ^{3}H, ^{10}Be, ^{14}C, ^{36}Cl, ^{41}Ca, ^{59}Ni, ^{60}Co, ^{63}Ni, ^{85}Kr, ^{90}Sr, ^{93}Mo, ^{93}Zr, ^{99}Tc, ^{94}Nb, ^{129}I, ^{135}Cs, ^{137}Cs, ^{152}Eu, ^{226}Ra, ^{232}Th, ^{237}Np and isotopes of U, Am, Pu and Cm.

Suitable matrices have been designed and estimates conducted of the properties of the waste for the calculation of the source term (leachability, stability) for each type of waste. The results are presented in a report by Čubová et al. (2017).

In order to calculate the amount of waste produced from the decommissioning of nuclear power plants, it is necessary to verify the data concerning the amount of radionuclides produced by activation. For this purpose, the unique opportunity was taken to perform the radiochemical analysis of real samples of irradiated concrete from the decommissioned Greifswald nuclear power plant, which was of the same type as the Dukovany nuclear power plant. The results are presented in a report by Svoboda et al. (2017).

The update of the inventory of ILW intended for disposal in the DGR served to expand the existing database, which divides ILW according to category. Moreover, it allowed for the determination of the amount of waste attributable to each power plant and other nuclear facilities.

Tab. 6 to Tab. 9 summarise the mass balances of the technological components of the reactor for one Temelín NPP unit, one Dukovany NPP unit and 1 NNS unit (immediate decommissioning variant) and the amount of RAW from the LVR-15 reactor.

Tab. 6 Inventory of the mass of ILW expected to be disposed of in the DGR for 1 ETE unit; gradual decommissioning variant (Podlaha et al. 2023a)

Component	Mass (tonnes)
Core sheath	35.0
Reactor shaft	58.1
Pressure vessel coating	22.7
Reactor pressure vessel	204.0
Heat insulation	20.5
Serpentinite concrete in front of the ionisation channels	32.1
Serpentinite concrete internal cladding	22.6
Fuel assembly steel supports	10.2
Block of protective tubes	17.1
Ionisation chamber channels	5.3

Component	Mass (tonnes)
Support ring	11.4
Structural concrete cladding under serpentinite concrete	1.4
Activated components - sensors, cables	4.3
Total (rounded up to whole tonnes)	**444**

Tab. 7 Inventory of the mass of ILW expected to be disposed of in the DGR for 1 EDU unit; gradual decommissioning variant (Podlaha et al. 2023a)

Component	Mass (tonnes)
Reactor shaft	53.0
Core basket	8.8
Inner surface of the pressure vessel	10.1
Heat insulation	14.0
Serpentinite concrete	38.5
Bottom of the core basket	13.2
Outer surface of the pressure vessel	90.9
Serpentinite concrete edge of the active zone	38.5
Block of protective tubes	18.0
Serpentinite concrete internal cladding	4.0
Inlet and outlet pipes up to 1 m from pressure vessel	8.0
Activated structural concrete	200.0
Activated components - sensors, cables	14.3
Total (rounded up to whole tonnes)	**511**

Tab. 8 Inventory of the mass of ILW expected to be disposed of in the DGR for 1 NNS unit; immediate decommissioning variant (Podlaha et al. 2023a)

Component	Mass (tonnes)
Steel	488.1
Other (activated components from operation)	5.1
Serpentinite concrete	38.5
Total (rounded up to whole tonnes)	**532**

Tab. 9 Inventory of the mass of ILW expected to be disposed of in the DGR from the decommissioning of the LVR-15 reactor (Podlaha et al. 2023a)

Component	Mass (kg)
Reactor vessel with stainless steel fittings (it is expected that only the lower part of the vessel will be disposed of in the DGR)	4,220
Aluminium reactor vessel fittings	387
Control rods	10
Beryllium reflectors (standard blocks: 27 items, atypical blocks: 6 items)	14,815
Parts of loops, probes, irradiated channels	
Total	**19,432**

The ILW that is currently stored at the Richard repository due to its not meeting the limits and conditions for acceptability for disposal in near-surface repositories will also be disposed of in the DGR. The total mass of this waste is 71,800 kg (as of 31 December 2021). Furthermore, sources of ionising radiation, especially ^{241}Am and ^{239}Pu type sources, must also be taken into account for disposal in the DGR. The sealed radioactive emitter database managed by the SÚJB (Sources Department) lists 6,115 items with a total activity of $2{,}16 \cdot 10^{16}$ Bq (as of 12 May 2022). The number of concrete WPs with disposed of sealed radioactive emitters will depend on how many emitters will be returned to the supplier for recycling and how many will be used for the production of radiopharmaceuticals or for other purposes. It will also depend on the user turnover of emitters.

5.3.2 Ongoing and planned work

Due to the uncertainty surrounding how many NNS and small modular reactors will be approved and when their construction will commence, the actual lifespans of the NPPs and the SNF storage time, it will be necessary going forward to focus on the analysis of the various options in terms of the development of nuclear energy. Currently, the preparation of documentation and analyses is underway that will serve to evaluate the impacts of the various options on the amounts of SNF and other RAW, and thus on the number of WPs and the dimensions of the two parts of the DGR.

Work in the subsequent period will focus on the following activities:

1) calculations of the RAW inventory for various scenarios in the development of nuclear energy with the consideration of the proposed storage periods and the analysis of uncertainties in terms of the operational periods of NPPs and the types of NNS and small modular reactors. With respect to all the above, analyses of the degree of conservatism, which impacts the overestimation (underestimation) of the results, must be performed. The results will influence the dimensioning of the DGR.
2) the analysis of the latest findings on the instant release fraction of radionuclides, which is an important factor in terms of the quantitative evaluation of the source term. This issue must be addressed at the international level since it requires the conducting of very demanding and expensive experiments (activity-related research),
3) the comparison of the results with the real operation of nuclear power plants. The research will allow for the comparison of the results obtained via the DGR preparation project with the current SNF inventories of the Temelín and Dukovany NPPs and the subsequent refinement of the data. The comparison of calculations with real operating conditions will make it possible to prove the suitability of the approach and allow for the proposal of the optimal approach to the emplacement of SNF in the DGR from the point of view of the temperature distribution.

The expected schedule of the key activities planned up to 2028 in this research area is shown in Tab. 10.

Tab. 10 Estimated schedule of activities planned up to 2028 concerning the RAW inventory for the DGR; indicative schedule showing continuity (outputs to) with key SÚRAO activities according to Tab. 1 in the right-hand column

Activity	FROM	TO	Outputs to
Calculation of the RAW inventory for various nuclear energy development options	2022	2024	1
SNF inventory update	2022	2024	1
Analysis of the latest findings on the instant release fraction of radionuclides	2022	2024	1
Comparison of the inventory results with the real operation of nuclear power plants	2022	2024	1

5.3.3 Future work

One of the long-term research tasks concerns the assessment of the cladding of SNF, which is important in terms of the design of the SNF handling method in the hot chamber. The assessment will include the analysis of extraordinary events and their probability and impacts on working in the hot chamber. It will be necessary to draw up technical and administrative measures that address extraordinary events. This will affect the equipment used in the hot chamber and the approach to dealing with damaged SNF. Planned future work:

1) the analysis of the situation concerning the cladding of SNF from the point of view of the operational and long-term safety of the DGR and the extended storage variant. The work will focus on the technical requirements for the equipment in the DGR related to the transport and handling of fuel and WDPs. Research on the cladding of SNF will monitor both the fuel in operational reactors and new types of fuel that are expected in the future. Concerning new ATF (Accident Tolerant Fuel, Běláč, 2022) fuels, it will be necessary to consider both the higher burn-up rate and longer fuel cycle times.
2) the evaluation of options for dealing with damaged fuel assemblies (design of an in-house container for damaged fuel assemblies, treatment of damaged fuel assemblies) and the proposal of measures concerning the hot chamber in case of damage to fuel assemblies during their transfer to WDPs.

5.4 Geological characterisation of the candidate DGR sites and the selection of the final and backup sites

The geological characterisation of the sites is aimed at determining the maximum amount of information regarding the geological environment of the sites and obtaining the information required on the sites necessary for the construction of site descriptive models (Valter et al. 2023, TZ 705/2023). These models will serve for the synthesis of the information and data obtained from geological survey and research work on the surface and measurements from deep boreholes. The analysis and research of drilling cores will also provide an important source of information. The models will include the geological structure and its manifestation on the surface and will include the consideration of ongoing natural processes that have their origin in the Earth's geological past and that conditioned the current structure of the geosphere and its connections to surface ecosystems. The creation of the site descriptive models will involve a multidisciplinary interpretation approach in the following areas:

- geology and structural geology,
- the mechanics of the rocks and their thermal properties,
- hydrogeology,
- hydrogeochemistry,
- the transport properties of the rock mass and
- geodynamic phenomena (seismotectonic phenomena).

The site descriptive models will provide for the visual-mathematical descriptive characterisation of the sites and their regional contexts including the full range of relevant geosphere and surface ecosystem components. The models will also provide important input information for the DGR project design solution and for assessing the long-term safety of the sites.

The construction and regular updating of the site descriptive models will involve the conducting of extensive geological characterisation work. The work will include the application of geological research and survey methods as set out in Act No. 62/1988 Coll., the implementation of which will be determined by the specific crystalline rock environment at the given site. The key parameters of the rock environment from the DGR viewpoint, which comprise essential inputs for the site descriptive models, comprise (see Nahodilová et. al. (2022)):

1. Properties of the candidate sites - initial state
    a. Properties of the rock mass
    b. Petrological descriptions of the various lithological types
    c. Spatial distribution of the lithological types
2. Characteristics of brittle structures
    a. Faults
    b. Fracture systems
3. Geothermal characteristics of the rock environment
    a. Thermal parameters important for heat transfer in the rock environment
    b. Thermal parameters of the rock mass important for the removal of heat from the DGR
4. Geomechanical characteristics
    a. Geomechanical properties
5. Geochemical characteristics
    a. Geochemical composition of the lithological types
    b. Presence of unstable accessory minerals during the monitoring of the development of the DGR environment
    c. Character of the rock environment due to exogenous phenomena (character of the regolith)
    d. Alteration of rocks due to influences of endogenous origin (hydrothermal and pneumatolytic alteration of minerals and rocks, including the surroundings of brittle structures)
6. Hydrogeological properties
    a. Hydraulic pressure
    b. Permeability of the rock environment
    c. Magnitude of flows

   d. Character of the drainage base
7. Transport characteristics
   a. Fracture geometry
   b. Fracture surface properties
   c. Properties of the rock matrix
   d. Groundwater composition
   e. Gas composition

5.4.1 Work performed

The process of selecting a site for the construction of a DGR in the Czech Republic has been underway with minor interruptions since the 1990s. The original idea of exporting nuclear waste to the former USSR turned out to be both legally and ethically unacceptable. Following political changes in Czechoslovakia in 1989, a strategic long-term plan to build the country's own DGR was adopted.

The first geological study was conducted by the then Central Geological Institute (now the Czech Geological Service) in 1989. Based on the geological structure of the Czech Republic, the presence of mineral deposits and findings from remote sensing, hydrogeology, seismicity, recent movements of the earth's crust, geophysics and engineering geology, 27 geological bodies were selected for further research. Most of the sites were located in acidic igneous rocks (granite and granodiorite), and to a lesser extent in basic and ultrabasic rocks (peridotite, diorite, gabbro, syenite) and metamorphic rocks (gneiss, phyllite, migmatite). In 1998, the Nuclear Research Institute Řež a.s. published its *Critical Review of Archived Geological Information* report (Woller et al. 1998).

The newly-established Radioactive Waste Repository Authority (SÚRAO) subsequently conducted a review of previous research and decided to supplement the research to date according to recommendations from the IAEA (IAEA 1994), which led to the compilation of a report entitled *Selection of the location and construction site for the DGR for RAW in the Czech Republic, Analysis of the Czech Republic, regional mapping phase* (Šimůnek et al. 2003). The assessment of the Czech Republic and the selection of sites for the construction of the DGR proceeded via several stages.

1. The 1st stage involved the exclusion of unsuitable areas due mainly to unfavourable geological conditions (tectonic failure and tectonic activity, seismic load, volcanism and post-volcanic activity, etc.), non-compliance with basic Czech social and legal rights and issues concerned with international agreements and obligations.
2. The 2nd stage concerned the selection of areas with suitable geological conditions following a thorough assessment of the geological structure of the Czech Republic and the definition of the rock types suitable for the disposal of radioactive waste. In view of the geological structure of the extensive Bohemian Massif, crystalline rocks (igneous and metamorphic) were preferred. This rock type prevails in a large part of the Czech Republic, whereas sedimentary rocks make up only a small part of the country's geology and their use for the siting of the DGR is limited by significant groundwater sources.
3. The 3rd stage involved the exclusion of certain areas due to legally defined exclusion criteria, i.e. Act No. 114/1992 Coll., SÚJB Decree No. 215/1997 Coll. and with concern to so-called protected interests.

4. The 4th stage concerned the application of a priority system (population density, land cover, gamma radiation in the rock environment, radon risks, etc.).

Eleven sites and one backup site were subsequently selected. Based on the conclusions of a final report on the siting process (Šimůnek et al. 2003), SÚRAO decided that the next stage of work would continue with respect to just six sites, all of which were situated in the same rock environment, i.e. crystalline (granitoid) rocks. The decision to consider just one rock environment was motivated mainly by efforts to concentrate the research on near and far interaction processes in just one rock type rather than to divide resources into several research directions. Three more sites were later added to the list of potential sites - a former uranium mine, and sites in the vicinities of the Czech Republic's two nuclear power plants; the Moldanubikum project was launched specifically with the aim of determining suitable DGR sites near to the nuclear power plants (Hanžl et al. 2018; Navrátilová et al. 2018a). The third subsequently added site was Kraví hora, which was also located in a crystalline rock environment (highly metamorphosed rocks - granulite, migmatite).

The nine potential DGR sites - Březový potok (granite), Čertovka (granite), Čihadlo (granite), Horka (durbachite), Hrádek (granite), Kraví hora (granulite), Magdalena (durbachite), Na Skalní (EDU-west - durbachite), Janoch (ETE-south - migmatitised pararules) - were investigated in detail in the period 2014-2019 (Fig. 7).

Geophysical research was considered the priority during this phase of the DGR development project - geophysical data was obtained from the DIAMO archive for the Horka, Kraví hora and Hrádek sites, in the vicinities of which large-scale surveys had been conducted in connection with potential uranium mining (Ondřík et al. 2016 a, b, Hlisnikovsky et al. 2018); the data was reinterpreted for the purpose of creating surface maps and 3D models (Fischer et al. 2017, 2019). Primary data obtained from aerial geophysical measurements taken as part of the GeoBarrier project was re-evaluated and the information obtained was compared with the latest SÚRAO data (Bárta et al. 2017). The final project of this phase comprised the *Geophysical work for the description of the geological structure of potential DGR sites in the Czech Republic* project, the main purpose of which was to provide supplementary data and knowledge on the geological structures of the sites, including more precise descriptions of the inherent uncertainties (Beneš et al. 2019, Duras a Bláha 2019, Hrutka et al. 2019, Jirků et al. 2019, Karous et al. 2019, Kašpar et al. 2019, Levá et al. 2019, Levý et al. 2019a,b, Nikl a Gürtler 2019).

The petrographic and basic mineralogical characteristics of the rocks at the potential DGR sites were described in a report by Franěk et al. (2018). As part of the Moldanubikum project, the various sub-varieties of the rock environments were described in detail from the petrographic and geochemical perspectives for the EDU west (Na Skalním) and ETE-south (Janoch) sites (Hanžl et al. 2017, Navrátilová et al. 2017). Evaluations of the petrographic and mineralogical compositions of the rock environments for the purpose of estimating the transport parameters were performed by Havlová et al. (2015).

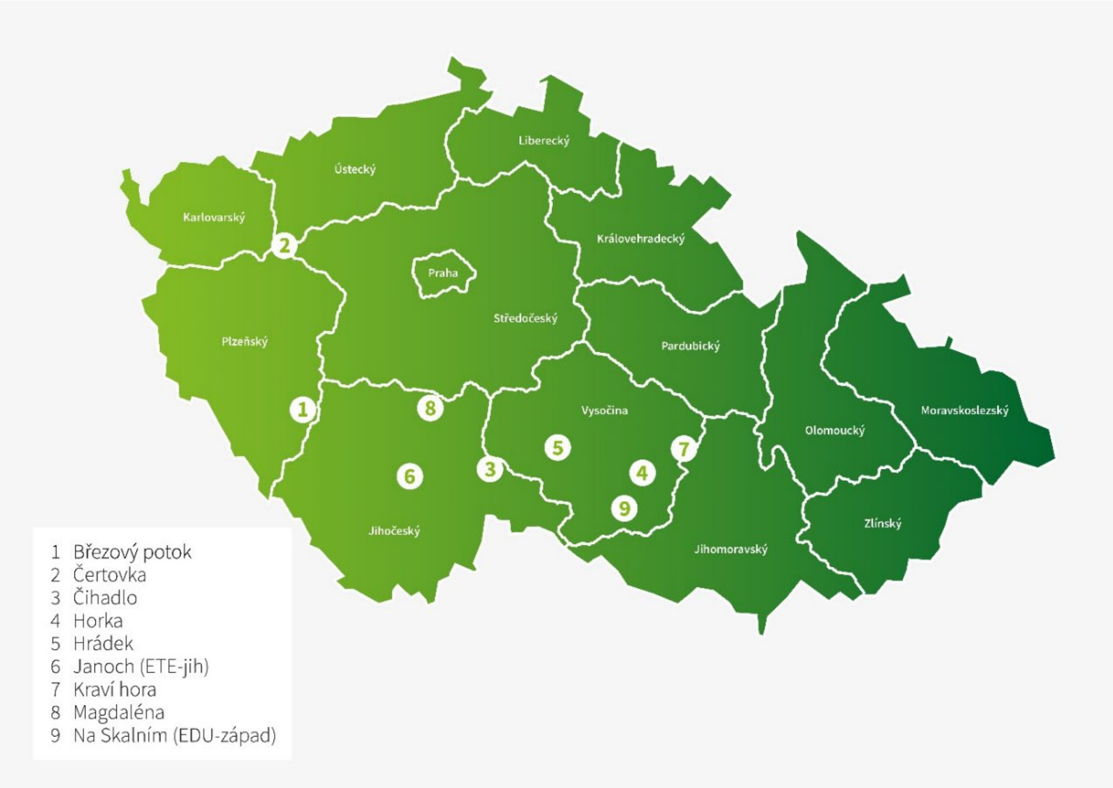

Fig. 7 Potential DGR sites in 2014-2019

Based on archived and newly acquired data (as described above), descriptive models of the sites were created (Franěk et al. 2018; Mixa et al. 2020; Baier et al. 2020 a, b; Černý et al. 2020 a, b; Jankovec et al. 2020 a, b; Polák M. 2020; Uhlík et al. 2020a,b), on the basis of which the sites were subsequently mutually compared (Vondrovic et al. 2020).

Following the detailed evaluation and comparison of the 9 sites in 2020, SÚRAO selected and recommended 4 sites to the government for approval - Březový potok, Horka, Hrádek and Janoch (ETE-south).

5.4.2 Ongoing and planned work

The aim of the geological research for the upcoming period is to expand the sets of data and information already available, which will serve to enhance the level of knowledge of the geological structures of the four selected sites (Březový potok, Hrádek, Horka and Janoch) and the relevant rock environments. Based on the outputs of this research, the existing site descriptive models will be refined in terms particularly of inputs for the project design solutions and long-term safety assessments. The new information will also allow for the more accurate determination of suitable rock blocks for the DGR. The existing 3D geological models of the sites (Franěk et al. 2018; Mixa et al. 2020; Baier et al. 2020a,b; Černý et al. 2020a,b; Jankovec et al. 2020a,b; Polák M. 2020; Uhlík et al. 2020a,b) and new data from the sites will form the key inputs for updating the site descriptive models. The expansion of the geological knowledge of the potential sites will primarily involve the inclusion of data obtained from boreholes and specialised geological research methods (e.g. deep geophysics, deep probes, seismic monitoring), which have not yet been applied to such an extent at the sites. The planned research is aimed at obtaining data from at least the depth of the DGR disposal horizon.

In order to fulfil the research objectives, it will be necessary to obtain data from the sites via a wide range of approaches (see Tab. 11), including the petrological description of the various lithological types found at the sites and the spatial distribution of the various lithological types and the determination of the presence of faults and fractures, the thermal properties important for the transfer and removal of heat in the rock environment, the geomechanical properties, the geochemical characteristics including the geochemical variability, the presence of potentially unstable accessory minerals, alteration via endogenous influences and the influence of weathering. Furthermore, it will be necessary to determine the hydrogeological properties – hydraulic pressure, the permeability of the rock environment, flow magnitudes, the nature of the drainage base, and the transport properties – the geometry and surface properties of the fracture systems, the properties of the rock matrix and the composition of the groundwater. In order to define the rock environment, a classification index of the suitability of the rock environment will be compiled, which will include, in addition to the geological characteristics, the geomechanical, hydrogeological and hydrogeochemical properties of the rock environment. The creation of the classification index will draw upon existing classification systems (e.g. Barton 1987, Bieniawski 1989, Andersson et al. 2000, McEwen 2002, Hagros et al. 2005, Hagros 2006) and the knowledge obtained from the study of the Bukov URF geological environment, see chapter 5.12.2.

The crystalline rock environment will largely determine the research methodologies applied for, and the overall character of, the future geological surveys of the 4 sites, the organisation of which will largely be based on the results of a previous project involving the research of a hypothetical site (TZ 390/20219, Mixa et al. 2019). Ongoing and planned geological research is described in greater detail in report TZ 652/2022 (Mixa et al. 2022). More precise definitions will be defined, and the approaches to performing the geological research will be described, in the geological research projects for each of the 4 sites, which are currently in the completion stage in the context of obtaining licences for the definition of exploration areas. A basic diagram of the progress of the geological research and the interconnection of the research themes is shown in Fig. 8. A number of activities have already commenced in partnership with the CGS (SO2021-110, see the Appendix).

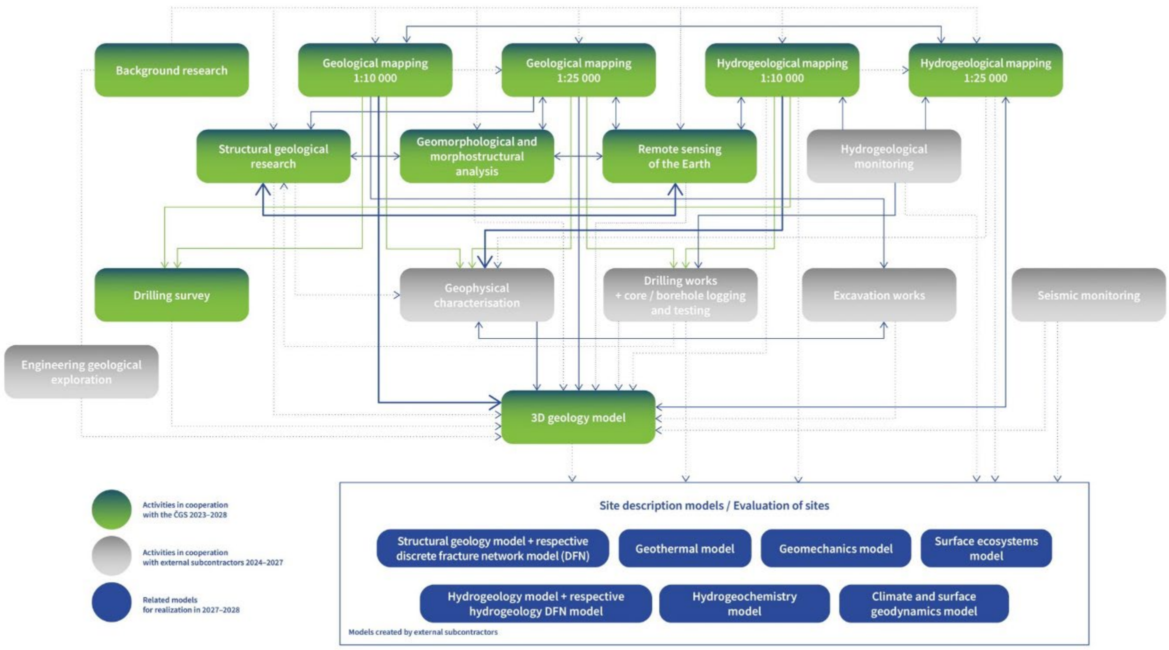

Fig. 8 Scheme of the geological research up to 2028

Tab. 11 lists all the key research activities and the expected schedule, the realisation of which is dependent on the granting of licences for exploration areas for special intervention into the earth's crust, which was expected at the beginning of 2024; however, at the time of the compilation of this report (April 2024), these licences had still not been granted.

Tab. 11 Estimated schedule of activities planned up to 2028 with concern to the geological characterisation research (see Mixa et al. 2022)

Activity	FROM	TO
Geological mapping 1:25,000	2023	2027
Hydrogeological mapping 1: 25,000	2023	2027
Structural-geological surveys	2023	2027
Geomorphological, morpho-structural research	2023	2027
Remote surveying	2023	2027
Hydrogeological monitoring	2024	2028
3D geological models	2023	2027
Geological mapping 1:10,000	2024	2027
Hydrogeological mapping 1: 10,000	2024	2027
Seismological monitoring	2024	2027
Geophysical research	2024	2027
Borehole research and testing	2024	2026

Activity	FROM	TO
Monitoring in boreholes	2025	2028
Engineering-geological surveys	2025	2026
Engineering-geological models	2027	2027
Geothermal models	2027	2028
Geomechanical models	2027	2028
Hydrogeological models and associated fracture network models (HG DFN)	2027	2028
Hydrogeochemical models	2027	2028
Climate and geodynamic process models	2027	2028
Surface ecosystem models	2027	2028
Descriptive models of the 4 sites	2027	2028

5.4.3 Future work

Following the selection of the final and backup sites, monitoring work will continue at the sites and further data will be collected that will allow for the more detailed descriptions of the sites for the planning of the construction of the DGR and the assessment of its long-term safety.

5.5 Project design and preparation for the construction of the DGR

DGRs comprise a specific type of nuclear facility; they feature two operational parts with differing activities in terms of the management of radioactive substances and differing requirements for the lifespans of the structures and equipment. The first operational part comprises the structures, equipment and technological infrastructure required to ensure the operation of the DGR, i.e. with respect to the acceptance and transfer of SNF to WDPs and RAW to WPs and the loading of SNF and RAW, which can be located in surface or near-surface facilities. The second operational part comprises the underground disposal areas. In terms of nuclear legislation, the requirements for nuclear facility projects of all types are set out in general in the Atomic Act (Act 263/2016 Coll.) and in more detail in related Decree. No. 329/2017 Coll., on requirements for nuclear facility projects. The main difference between DGRs and other nuclear facilities is that DGR projects depend significantly on the characteristics of the site at which they are to be constructed.

The Czech DGR must be designed in such a way that it is possible to safely dispose of all the country's radioactive waste, existing and planned, that is unacceptable for disposal in near-surface repositories (including SNF that is declared as waste in the future) according to the strategic priorities of the Czech Republic. The construction of the repository must be feasible at the selected site using proven technologies that are currently available, and radiation protection must be optimised so as to ensure the highest possible level of safety.

5.5.1 Work performed

In accordance with the Medium-term plan (Pospíšková et al. 2015), studies were completed on the suitability/feasibility of the DGR at the candidate sites – Březový potok TZ 139/2017 (Špinka et al. 2018c), Horka TZ 137/2017 (Bureš et al. 2018), Hrádek TZ 138/2017 (Špinka et al. 2018b) and Janoch TZ 222/2018 (Navrátilová et al. 2018b). The purpose of these studies was to verify the fulfilment of selected project criteria at the sites and included the conducting of reference project. The *Optimisation of the underground parts of the DGR reference project* – TZ 134/2017 (Grünwald et al. 2018h), which was conducted simultaneously, considered the concepts behind the individual reference technical solutions in more detail and concentrated the results in one joint report. It also considered the development of changes in the input parameters, especially the source term, the amount of waste, the storage period and the parameters of the disposal system materials and the rocks at the candidate sites, i.e. primarily the mechanical and thermal properties of the rocks and the bentonite and the thermal performance of the WDPs. The suitability studies were subsequently updated in 2020 – Březový potok TZ 514/2020 (Špinka et al. 2020b), Horka TZ 512/2020 (Butovič et al. 2020), Hrádek TZ 513/2020 (Špinka et al. 2020a) and Janoch TZ 518/2020 (Zahradník et al. 2020).

Currently, based on Resolution No. 1350 of the Government of the Czech Republic dated 21 December 2020, preparatory work is underway at the four selected sites, i.e. Březový potok, Horka, Hrádek and Janoch. The technical design of the DGR, including the decision on the adoption of the vertical disposal method and the use of the conventional (drill and blast) excavation method, is described in TZ 711/2023 (Hausmannová et.al. 2023).

5.5.2 Ongoing and planned work

The objective of this period concerns the synthesis of the outputs from all the R&D sub-areas required for the compilation of the first version of the initial project. Project design-related R&D work will consist mainly of the following activities:

- the identification and summarising of DGR project requirements (Design Basis, Design Requirements) in accordance with the requirements of Decree No. 329/2017 Coll. - this stage will be coordinated as part of the preparation of the requirements management system so that the project requirements and assumptions include all the factors that determine the design of the DGR, legislative requirements and recommendations from international organisations,
- the thermal dimensioning of the DGR for the specific conditions of the selected sites for various DGR layout options,
- the determination of approaches to the transport of RAW from generators to the DGR and the connection of the DGR infrastructure to existing rail and road connections
- the determination of the method for transferring SNF from storage and transport containers to WDPs,
- the conceptual design of the handling technologies for the emplacement of WDPs with SNF in the disposal wells,
- an alternative method for the selection (siting) and specific arrangement of the surface part of the DGR,
- the updating of the technical design solution,

The objective of the research in this period is to update the technical design of the DGR and to create new siting studies for the 4 sites. It is assumed that the reference design solution will be sufficiently flexible so as to allow for modifications in the subsequent stages of the project documentation taking into account the specific conditions at the final site with the aim of ensuring the highest levels of nuclear safety and radiation protection in all the phases of the DGR lifespan. New siting studies should include the updating of the geological and hydrogeological properties – e.g. the size of the usable rock mass, the fault structures and the fracture systems, the thermophysical properties etc. The layouts of the underground complex and the surface area will be modified accordingly. The interconnection between the site characteristics and the technical design will be discussed in detail in the Design Basis work. Some parts of the technical design will be updated only for the final and backup sites following the completion of the selection process, which means that certain simplifications included in the reference design solution can be used in the siting studies, which would subsequently be modified in the technical solution according to the specific site characteristics in the next stage.

The development of the project design solution also includes the following areas, which, due to their importance, are described separately later in this report:

- research and development of the WDP and related technologies (chapter 5.7)
- research and development of the (back)fillings of the disposal wells and tunnels and related technologies (chapter 5.8) and
- research and development of other engineered components (chapter 5.9).

During this period, all the research conducted by the project and engineering activities departments will focus on the compilation of materials that will serve to support the selection of the final and backup sites - siting studies on the individual sites.

The updating of the DGR life cycle schedule will be conducted in connection with the adoption of the Taxonomy conditions, as will the updating of the structures in the surface area and its final siting at the specific candidate sites and the updating of the technical design of the DGR (including an evaluation of the operational safety of the proposed technical design variants for the disposal systems and related technologies); studies will be performed of the economic and socio-demographic benefits and risks of the construction of the DGR in terms of the development of the affected regions.

An overview of ongoing and planned key activities for the period up to 2028 is provided in Tab. 12.

Tab. 12 Estimated schedule of activities planned up to 2028 concerning the DGR project design solution; indicative schedule showing continuity (outputs to) with key SÚRAO activities according to Tab. 1 in the right-hand column

Activity	FROM	TO	outputs to
Update of the DGR life cycle schedule in connection with the acceptance of Taxonomy conditions	2023	2024	2
Final localisation of the surface areas at the selected sites	2023	2025	4
Studies of the economic and socio-demographic benefits and risks of the construction of the DGR	2022	2025	3
Processing of the concept and support for the implementation of the BIM methodology for the DGR project	2024	2027	11

Activity	FROM	TO	outputs to
Validation of the thermal dimensioning model of the DGR for SNF	2023	2024	11
Handling, technology and transport strategies	2024	2026	11
Visualisations of the surface areas	2025	2026	4
Update of the technical design of the DGR	2024	2027	11
Siting studies	2027	2029	14

5.5.3 Future work

Following the approval of the final and backup sites, feasibility studies will be prepared for the two sites based on the previously compiled siting studies. The feasibility studies together with the initial project (basic) designs will serve as the basis for the drawing up of the licence documentation. The initial project will include a geotechnical survey. The licence documentation will demonstrate to the relevant state administration bodies that the DGR is technically feasible and that, from the safety point of view, the changes and processes that will occur in the rock environment and the biosphere will exert no negative impacts on the DGR and, thus, that the DGR will not endanger human health and the various components of the environment.

Based on the **feasibility studies** (for the final and backup sites), the licence documentation will be drawn up for:

- The EIA process, documentation according to Act No. 100/2001 Coll., Appendices 3 and 4,
- Territorial planning documentation,
- Licence for the siting of a nuclear facility according to section 9 paragraph 1 letter a) Act No. 263/2016 Coll. and documentation according to Act No. 263/2016 Coll., Appendix No. 1, part 1 letter a); this licence will serve as the initial licence under the Atomic Act and will precede the other licencing processes (construction and mining).
- Determination of protected areas for special intervention into the earth's crust, documentation according to Czech Mining Authority Decree No. 364/1992 Coll.,
- Framework licence, documentation according to Act No. 283/2021 Coll., section 158.

This will be followed by the compilation of **construction licence documentation** for:

- The mining activity licence for the underground part of the DGR (technical equipment/infrastructure in excavated sections and the construction of the underground part of the DGR, in connection with activities already conducted on the basis of the notification of mining-related exploration research or as part of the geological survey research),
- The mining activity licence for the construction of the nuclear facility area (excavation and installation of the technical infrastructure for the preparation and disposal sections, main corridors, loading corridors and disposal wells depending on the disposal method, i.e. structures that are defined as part of the nuclear facility according to Act

No. 263/2016 Sb., i.e. they fulfil an operational function and are thus not part of Building 4).

- Planning permission for the construction of the surface part of the DGR
- Licence for the construction of a nuclear facility, documentation according to Appendix No. 1, Part 1, letter b) of Act No. 263/2016 Coll.,
- Documentation for the construction of the individual buildings included in the DGR project.

This will be followed by the compilation of the **construction documentation**.

From the point of view of authorisation for nuclear facilities, the compilation of the following will be required:

- documentation for a licence for the commissioning of a nuclear facility without a nuclear reactor; documentation according to Appendix No. 1, part 1, letter e) of Act No. 263/2016 Coll.,
- documentation for a licence to implement changes that impact nuclear safety, technical safety and physical protection; documentation according to Appendix No. 1, part 1, letter h) of Act No. 263/2016 Coll.,
- documentation for a licence to operate a nuclear facility; documentation according to Appendix No. 1, Part 1, letter f) of Act No. 263/2016 Coll.

5.6 Impacts of the DGR on the environment

The siting of the DGR should not create any obvious (difficult-to-remove) conflicts of interest in the selected area that indicate significant long-term threats, potential excessive damage to particularly sensitive ecosystems or the deterioration of the condition of individual components of the environment with negative impacts on human health. According to IAEA recommendations (IAEA 2011b, I.44-I.47), the DGR should be sited in such a way that the quality of the environment will be sufficiently protected and potential negative impacts can be mitigated to an acceptable degree, taking into account technical, economic, social and environmental factors.

This must be proven by evaluating the impacts of the construction of the DGR at a given site on the various components of the environment (soil, water, air, landscape character, fauna, flora, ecosystems, climate), public health, natural resources, cultural monuments etc.

The aim of the various research projects, studies and activities is to collect relevant information, knowledge and arguments regarding:

- the DGR project design solution (identified conflicts of interest and potential impacts on the environment form two of the inputs for the localisation of the DGR surface area, including the related transport and technical infrastructure),
- the assessment of the quality of the land, the so-called zero state of the land,
- inputs to the ecosystem model and
- the evaluation of sites for the purpose of selecting the final and backup sites.

5.6.1 Work performed

A number of studies and documents were prepared for the defined exploration areas in 2014-2022, the results of which were summarised in the form of technical reports.

They concerned primarily:

- Site suitability/feasibility studies (Bureš et al. 2018a; Špinka et al. 2018b-c; Navrátilová et al. 2018b)
- Study of impacts on the environment (Marek 2018b-d; Navrátilová et al. 2018c)
- Monitoring of water sources, water bodies and watercourses (Říčka et al. 2018, Šedivá 2018, Černý and Šedivá 2018,
- Socioeconomic analyses (Hampl et al. 2017, Hampl and Hůle 2018)
- Monitoring of the air with respect to radon and ionising radiation in places of known anomalies (Froňka and Fojtíková 2017)
- Initial safety report study (Vokál et al. 2018a-d)
- Explanatory report – Localisation of protected areas (Pertoldová et al. 2019)
- Analysis of natural accumulations of underground and surface water in the broader area of interest of the DGR from the point of view of their use as drinking water sources (Krajíček et al. 2020 – Appendix No. 2)
- Biology I (Pravec et al. 2022)
- Analysis of biosphere FEPs (Hušťáková et al. 2022)

The research was performed at all nine sites - Březový potok, Čertovka, Čihadlo, Horka, Hrádek, Janoch, Kraví hora, Magdaléna and Na Skalním up to 2020 and, after the reduction in the number of sites to four (Resolution of the Government of the Czech Republic of 21 December 2020 No. 1350), at the Březový potok, Horka, Hrádek and Janoch sites only. The reports cited above refer primarily to the latter four selected sites.

The results of the research formed one of the inputs for the site evaluation process conducted in 2020, based on which the number of sites was reduced from nine to four.

5.6.2 Ongoing and planned work

The aim of the upcoming stage concerning environmental issues will involve mainly:

- updating and supplementing existing information on the environment and the population,
- expanding research activities with field measurements and observations,
- determining inputs for the surface area localisation methodology,
- preparing two studies connected with Annex No. 4 of the Act on the Assessment of Impacts on Environmental Protection (Act No. 100/2001 Coll.), namely: i) the impact of geological exploration work on environmental protection and public health and ii) the impact of the proposed DGR design solution on the environment and public health and
- determining arguments for negotiations with affected municipalities.

Planned activities up to 2028 concerning the environment are listed in the following table, along with an indicative schedule. A number of research tasks aimed at fulfilling the aims defined above will be performed as part of the “Research support for the project design of the deep geological repository for the safety assessment of the disposal concept" project (see attachment no. 1); the other projects will be conducted by sub-contractors via the standard public tendering procedure (as marked in the table).

Tab. 13 Estimated schedule of activities planned up to 2028 concerning the environmental impact assessment of the DGR; indicative schedule showing continuity (outputs to) with key SÚRAO activities according to Tab. 1 in the right-hand column

Activity	FROM	TO	Outputs to
Biological screening	2023	2024	13
Update on conflicts of interest at the four sites	2024	2024	13
Methodology for the localisation of the surface areas	2024	2024	13
Assessment of the impact of geological surveys on the environment and population ("EIA GP Study")	2023	2024	9
Description of the components of the biosphere as one of the inputs for the ecosystem models)*	2024	2025	13
Study on the management of excavated material	2025	2026	13
Noise study)*	2026	2027	13
Dispersion study)*	2026	2027	13
Health risk assessment)*	2027	2027	13
Detailed biological survey	2026	2027	13
Evaluation of the impact on the landscape	2026	2027	13
Assessment of the influence of the DGR on the state of surface and underground water courses/bodies)*	2026	2028	13
Dendrological survey)*	2028	2029	13
Pedological survey)*	2028	2029	13
Assessment of the impact of the DGR on the environment and the population ("EIA Study" of the DGR) - background studies of the selected sites	2027	2029	13

)* activities that do not form part of the "Research support for the project design of the deep geological repository for the safety assessment of the disposal concept" project

Biological screening

The aim of the screening is to describe the demarcated areas (exploration areas for special intervention into the earth's crust) according to the quality of the natural environment and to provide framework information on the nature of the biotopes and fauna and flora for the purposes of the design of the detailed biological survey, which will subsequently be conducted in the exploration areas.

Update on conflicts of interest at the four sites

The aim is to identify or to update conflicts of interest and territorial limits in the following areas: natural conditions and protected natural areas, technical and transport infrastructure, settlements and the population, cultural and historical value of the area, functional use of the land, development plans in the area.

Assessment of the impact of geological surveys on the environment and population ("EIA GP Study")

This forms the basis for negotiations with the affected municipalities and state administration authorities as part of the process for determining exploration areas for special intervention into the earth's crust and the licencing of selected geological exploration work procedures (drilling and digging).

Condition A.1.6. Position of the Ministry of the Environment on the draft Update of the Management of Radioactive Waste and Spent Nuclear Fuel Concept (ref. MZP/2017/710/2721 dated 20 November 2017).

Provision of inputs for the ecosystem models

Ecosystem models are used to calculate the transport of radionuclides into the environment for various repository development scenarios, including the estimation of the maximum doses of the released radionuclides that can be received by a representative person.

One of the inputs comprises the specification of the biosphere components at all four sites. The components are: soil and sediments (agricultural land), aquifers and water layers (water distribution and storage system), water courses and water bodies, the local atmosphere, plant life (food and feed, food processing and storage), animals (livestock) , human community (local community - customs); see Huťáková et al. 2022.

Study on the management of excavated material

The study will include the assessment of placement options, the further use of excavated material and the parameters of the excavated material dump in connection with the relief of the landscape and visual exposure. A summary of quarries potentially suitable for the permanent disposal of surplus excavated material will be drawn up, including access distances.

Noise study

The aim of the noise study will be to assess whether the noise from the construction and operation of the DGR will exceed the public health limits defined for protected outdoor areas. Public health noise and vibration limits are set out in Decree No. 272/2011 Coll. Proposals for potential anti-noise measures will form part of the study.

The basis for the study will comprise information on the basic acoustic situation in the affected areas (the evaluation of traffic noise will be based on data from the Czech road and railway administration authorities) and information on all future sources of noise.

Special software approved by the chief public health officer of the Czech Republic is used for evaluation purpose, fully respecting the Methodological instruction for determining the noise load from traffic in the Czech Republic and the Manual for the compilation of noise studies concerning rail traffic and for measuring noise from rail traffic.

The measurement of noise levels requires authorisation in accordance with section 83c of the Act on the Protection of Public Health (Act No. 258/2000 Coll.).

Dispersion study

The dispersion study is a document that, based on calculated model pollution values, serves for the assessment of the influence of the DGR (in all the phases of its life cycle), including transport structures and waste disposal activities, on the current level of air pollution in the affected area. It concerns the quantification of the emission and immission loads in the air. The basis for the compilation of the study comprises information on all emission sources (point, area, line) related to the repository, the state of the air in the area that will not include the repository as determined from ČHMÚ documentation, the ventilation factor of the area and the frequency of occurrence of wind with speeds of 2 m/s and below. The evaluation of the model is performed using a software program approved by the Ministry of the Environment according to the Ministry's methodological instructions.

Only persons authorised by the Ministry of the Environment in accordance with section 32 letter e) of the Air Protection Act (Act No. 201/2012 Coll.) are allowed to compile dispersion studies.

The results of the dispersion study will allow for the selection of suitable air monitoring measuring points (including the use of existing CHMÚ stations).

The dispersion study usually forms part of the EIA process.

Public health impact assessment

The assessment includes the determination of the types and degrees of potential danger according to defined physical, chemical and biological factors. The outputs consist of i) the assessment of the extent to which the affected population groups may be exposed to these factors and ii) the determination of the nature of the risks. The input for the assessment comprises primarily the noise and dispersion studies.

Health risk assessments can only be performed by **persons who hold a Certificate of Professional Competence in the area of public health impact assessments**.

The health risk assessment forms an integral part of the EIA process.

Detailed biological survey

The aim of the detailed biological survey is to set out information on the flora and fauna (ecological potential) in the area affected by the DGR. The survey includes migration studies, biotope assessments, the analysis of e.g. exceptions to the special protection of plant and animal species and recommendations for the reduction or elimination of the negative impacts of the DGR in the given area.

The biological survey forms the basis for the biological assessment in the sense of section 67 of Act No. 114/1992 Coll., on the protection of nature and the landscape (ZOPK). The assessment usually forms part of the EIA process and can only be performed by persons authorised according to section 45i of ZOPK. The requirements of the assessment are set out in section 7 of Decree. No. 142/2018 Coll.

Evaluation of the impact on the landscape

The aim of the evaluation is to assess the extent to which the DGR will affect the features and value of the landscape in accordance with section 12 of ZOPK. The evaluation concerns particularly the preservation of important landscape elements, the aesthetic values of the landscape, cultural features in the landscape and harmonious relationships within the landscape.

The evaluation is performed for so-called “potentially affected landscape areas”, which are designated by defining a circle of potential visibility and visual barriers (e.g. terrain horizons, edges of forests, etc.). The study normally consists of three parts: evaluation of the affected area (without the DGR), evaluation of the impacts of the DGR on the area, the proposal of measures.

Assessment of the influence of the DGR on the state of surface and underground water courses/bodies

The aim of the assessment is to assess whether and how the construction and operation of the DGR will affect the surface and underground water in the affected area with particular reference to groundwater sources, i.e. the hydrological conditions, hydrogeological characteristics, chemical state of the water and the water balance. It also includes a proposal for mitigation and/or compensation measures. Water management is regulated by Act No. 254/2001.

Information for the assessment will be taken from the Hydrogeological Monitoring project (see chapter 5.4.2).

Dendrological survey

The dendrological survey is used for the inventory (mapping) of tree species in the area of interest. The aim is to determine the species of trees present, the horticultural value, the dendrological characteristics, the health status of the trees, damage, stability etc.

The survey can only be performed by authorised architects in the field of landscape architecture according to section 4 of Act No. 360/1992 Coll.

The dendrological survey is <u>necessary in terms of decisions on permission to cut down trees</u> in accordance with Section 8 of ZOPK and implementing decree. No. 189/2013 Coll.

Pedological survey

The aim is to assess the soil conditions in the area of interest, i.e. to determine the soil quality (protection class), the physico-chemical and biological properties of the soils, contamination, the depths of the soil layers, the economic use/preservation of the overburden.

The pedological survey is necessary in terms of decisions on the withdrawal of land from the agricultural land reserve (ZPF) in accordance with section 9 of Act No. 334/1992.

Assessment of the impact of the DGR on the environment and the population ("EIA Study" of the DGR)

The study will be compiled according to the structure defined in appendix No. 4 of Act No. 100/2001 Coll. (parts: B, C, D, E) using the outputs of the studies and assessments described above. The assessment will concern primarily the DGR surface area and/or components thereof and their connection to the existing transport infrastructure.

The study will be beneficial in terms of negotiations with the affected municipalities and will form input for the EIA process (final and backup sites).

5.6.3 Future work

The priority of future work will concern the completion and potential supplementing of the documentation for the initiation of the EIA processes for the final and backup sites (the submission of requests for opinions according to section 45i paragraph 1 of ZOPK, the preparation of related assessments, the submission of notices of intention according to Appendix 3 of Act 100/2001 Coll., and the initiation of investigation proceedings).

The monitoring of the sites will follow the monitoring plan devised by Svoboda et al. 2019.

A more detailed description of future activities is provided in the update to Vozár et al., 2023.

5.7 Waste disposal packages

5.7.1 Waste disposal package for SNF

Waste disposal packages (WDP), which are "intended for the disposal of spent or irradiated nuclear fuel or radioactive waste resulting from its reprocessing", are defined in section 11, paragraph 1 letter e) of Decree No. 379/2016 as type D disposal packages. According to the decree, type D disposal packages must be:

1) sufficiently mechanically resistant in terms of the handling method and
2) made of materials whose service life corresponds to the projected service life of the WDP. Shorter lifespan materials can only be used for those parts of the WDP that can be easily replaced during the operation of the radioactive waste/spent nuclear fuel storage facility or the radioactive waste repository.
3) constructed in such a way that they comply with the limits and conditions for the handling of radioactive waste, including the relevant conditions of acceptability, as approved by the respective authority.

In order to fulfil the legislative requirements, the WDP must (Pospíšková et al. 2022a, Vrba et al. 2023):

1) ensure the practically complete isolation of the RAW[1] for a period that will result in the significant reduction of its initial activity, i.e. for a period of at least 10,000 years, but with an expected WDP lifespan of approximately 1,000,000 years,
2) ensure the physical prevention of the occurrence of critical and supercritical conditions during operation and following the closure of the repository, taking into account all the waste properties and the phenomena, processes and events that may occur,
3) ensure the prevention of the accumulation of heat and the negative influence of the disposed of SNF on the retardation capabilities of the surrounding barriers,
4) be able to withstand mechanical loading in the DGR, particularly at the disposal well locations for the defined period of time (types of material and their mechanical properties),
5) the corrosion resistance of the materials used must ensure the isolating function of the WDP for the defined period of time (types of materials, their chemical properties, wall thickness),
6) the materials used for the WDP must be compatible with the surrounding environment in order not to reduce the effectiveness of the other barriers.

The provision of these safety functions is ensured by the structure of the WDP and the selection of highly corrosion-resistant materials with high mechanical strength that are able to resist the hydrostatic pressure of the groundwater, the swelling pressure of the bentonite surrounding the WDP and potential movements in the rock mass. For the preliminary assessment, a horizontal displacement of 50 mm and a velocity of 1 m/s in the shear plane were chosen, which corresponds to an earthquake of magnitude 7-8 on the MSK-64 scale (POSIVA and SKB, 2017). Moreover, the design of the WDP must ensure that the SNF does not endanger either the safety functions of the WDP itself or the other disposal barriers due to the heat generated and the dose rate.

Various types of metallic and non-metallic materials have been tested in the past as potential suitable materials for the WDP. The reference WDP in the Swedish and Finnish concepts, which, as in the Czech concept consider crystalline rocks for the DGR, features a copper cover and a solid cast iron inner container. The main reason for choosing copper concerned the thermodynamic stability of copper in reducing environments without the presence of sulphides and sulphate-reducing bacteria, whereas the cast iron inner structure provides for the necessary strength. Due to the different crystalline rock environment in the Czech Republic, however, especially the lower content of chlorides in the groundwater, as well as for economic reasons, the Czech concept currently assumes the use of carbon and stainless steel, which should provide for the sufficient isolation of the SNF for the required period of time.

5.7.1.1 Work performed

Several SNF WDP concepts are being developed worldwide, the choice of which is largely dependent on the DGR rock environment. The requirements for WDPs intended for clay

[1] The term practically complete isolation means that only under very unfavourable conditions caused by the concurrence of exceptional events with a very small probability, a WDP may be damaged even before 1,000,000 years.

environments are generally less demanding than for WDPs for crystalline environments since the clay forms the main barrier against the leakage of radionuclides.

Research on WDPs has been underway as part of the Czech DGR development programme since 1995, when the first WDP concept was proposed by Škoda JS a.s. This WDP featured a thin-walled (5 mm) stainless steel inner casing and a carbon steel (6 cm) outer cover. However, this concept was considered unsuitable due especially to the low mechanical strength of the thin-walled stainless steel casing, which would likely be exposed to immediate damage from the hydrostatic pressure and bentonite swelling pressure in the DGR. Therefore, in 2013, an extensive research project named the *Research and development of a waste disposal package for the deep disposal of spent nuclear fuel to the sample realisation stage* (Forman et al. 2021) was launched. The project considered 13 variants for the disposal of fuel assemblies from the VVER 440 reactor and one comparative variant for fuel from the VVER 1000 reactor applying various materials (steel, copper, titanium).

Reference designs for WDPs for VVER 440 (WDP 440) fuel and VVER 1000 (WDP 1000) fuel emerged from the *Research and development of a waste disposal package for the deep disposal of spent nuclear fuel to the sample realisation stage*. The variant comprised a separate inner casing made of stainless steel (EN 1.4404) for each fuel assembly, which would ensure both corrosion resistance and mechanical strength. All the components of the inner casing are held together by a built-in stainless steel (EN 1.4404) framework, which will serve to ensure the stability of the individual assemblies and to maintain their distribution in the required geometry; it has no corrosion or strength function. Carbon steel (S355J2H+N) was chosen for the outer casing comprising a cylinder with a welded bottom and lid.

The diameter of the WDP 440 (Fig. 9) was set at 914 mm and the length at 3,790 mm. The thickness of the cylindrical part of the outer casing is 65 mm and the lid and bottom 200 mm. In addition, the lid is equipped with a valve covered by a plug in the outer casing welded to the lid of the WDP that will serve to control the gaseous environment within the WDP and/or the outer casing. The space inside will be filled with nitrogen (0.15 MPa).

The inner casing, as with the outer casing (in Fig. 9 and Fig. 10), comprises a cylinder to which the bottom and lid of the inner casing are welded. The thickness of the cylindrical part is 36 mm, the lid 130 mm and the bottom 75 mm. The lid, as with the outer casing, features a valve covered by a plug welded to the lid. The length is 3,364 mm. The inner casing will be filled with helium (0.1 MPa).

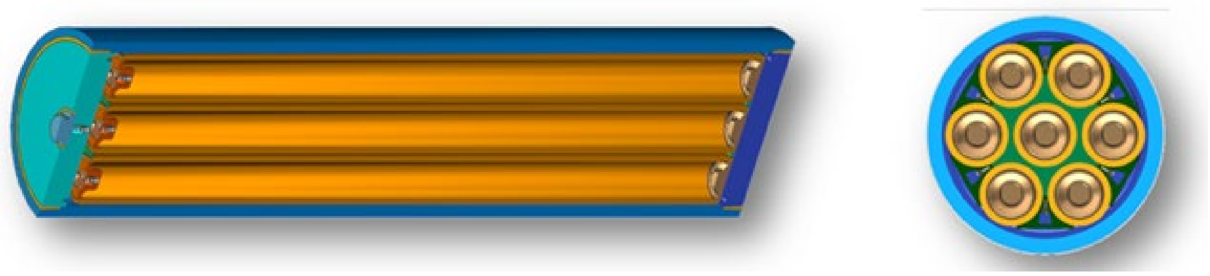

Fig. 9 Visualisation of the WDP assembly for VVER-440 fuel (WDP total length – 3,790 mm; WDP outer diameter – 914 mm). Blue – outer casing, orange – inner casing

The diameter of the WDP 1000 is 914 mm with a length of 5,205 mm (see Fig. 10). The outer casing consists of a cylinder with a welded bottom and lid. The thickness of the cylinder is 65 mm and the lid and bottom 200 mm. In addition, the lid is equipped with a valve covered by a plug in the outer casing welded to the lid of the WDP. The space inside the outer casing is filled with nitrogen (0.15 MPa).

The inner casing, as with the outer casing, consists of a cylinder to which the bottom and lid of the inner case are welded. The thickness of the cylinder is 40 mm, the lid 140 mm and the bottom 75 mm. The lid, as with the outer casing, is equipped with a valve covered by a plug welded to the lid. The length of the inner casing is 4,779 mm. The inner casing will be filled with helium (0.1 MPa).

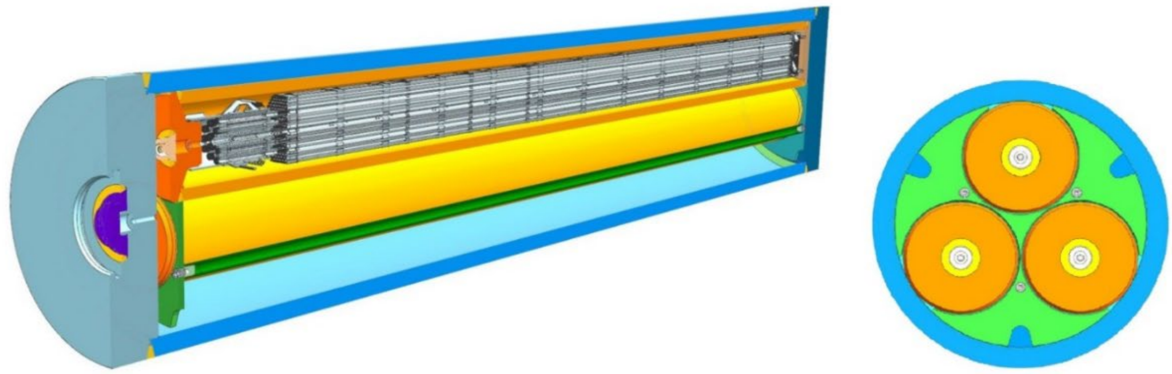

Fig. 10 Visualisation of the WDP assembly for VVER-1000 fuel with three stainless steel inner casings (WDP total length – 5,205 mm; WDP outer diameter – 914 mm). Blue – outer case, orange – inner case

Research and development work (Forman et al. 2021) on the most suitable materials for the inner casing led to the selection and comparison of two types of stainless steel - dual-phase steel EN 1.4462 and austenitic steel EN 1.4404

Dual-phase steel EN 1.4462 was considered due to its elevated Cr and Mo contents, which contribute to enhancing corrosion resistance. Austenitic steel EN 1.4404 was also chosen for its high corrosion resistance properties.

Although dual-phase steel EN 1.4462 has a higher content of Cr and Mo, the susceptibility of the two steel materials to pitting corrosion under DGR conditions was observed to be approximately the same (Stoulil et al. 2019). Due to the susceptibility of dual-phase steel to hydrogenation, and the associated loss of mechanical resistance, austenitic steel EN 1.4404 was the finally selected option due to its non-susceptibility to hydrogenation (Forman et al., 2021).

Carbon steel S355J2H+N was selected for the production of the outer casing. The advantage of this steel concerns the minimal content of carbide-forming elements, which limits the occurrence of localised corrosion (pitting corrosion) compared to the other steel materials that were shortlisted for the production of the outer casing of the WDP.

With concern to stainless steel, it is necessary to ensure conditions under which the temperature following the loss of the functionality of the outer casing is lower than the critical temperature, which has been experimentally verified at 40°C (Stoulil et al. 2024). At temperatures lower than the critical temperature, stainless steel is guaranteed to exhibit enhanced resistance to corrosion. Furthermore, the surrounding environment must be anaerobic and without higher concentrations of chlorides, which could accumulate on the surface of the WDP at higher temperatures.

The expected number of WDPs is 7,600 (Hausmannová et al. 2023): 3,100 VVER 440 WDPs, 1,800 VVER 1000 WDPs and 2,700 NNS WDPs. Hence, mass production will be required rather than unit production, a further factor that must be considered in the design of the WDP.

Significant results were provided via the MACOTE international project (Zuna et al. 2023) conducted at the Grimsel underground laboratory in which both carbon steel and copper samples were studied in situ. Local corrosion was observed on all the carbon steel and copper samples. The project clearly demonstrated the need to conduct experiments in the real environment of underground laboratories at elevated temperatures. The results showed that the corrosion rates of carbon steel (12022) produced by Železiarne Podbrezová, Slovakia) decreased after the first two years followed by the relative stabilisation of the corrosion rate. The highest average corrosion rates for carbon steel were obtained for the BaM bentonite (21.4 ± 3.1 µm/year) and MX-80 bentonite (18.6 ± 1.8 µm/year) environments after the first year of the experiment. After two years of experimentation, the average corrosion rate of the carbon steel had decreased by 14.1 ± 2.1 µm/year for the BaM bentonite and 13.5 ± 1.1 µm/year for MX-80. The corrosion rate between 3 and 7 years was calculated at around 9.5 ± 2.2 µm/year (BaM) and 6.5 ± 1.9 µm/year (MX-80). Siderite and chukanovite were identified as corrosion products on the samples.

In order to verify the lifespan of the DGP, i.e. 1,000,000 years, data must be obtained from long-term in-situ experiments (which last at least 10 years) and archaeological and natural analogues, concerning which the *Pilot Corrosion Experiment* (see Appendix 1, SO2020-086) project is currently underway and the *Archaeological analogues for the verification of container lifetime models for deep geological radioactive waste repositories* (Stoulil et al. 2022) and *Processing of samples from corrosion experiments - Corrosion products 2* (Stoulil et al. al. 2023) projects were completed recently.

The *Archaeological analogues for the verification of container lifetime models for deep geological radioactive waste repositories* project (Stoulil et al. 2022) obtained data from 15 archaeological sites and more than 200 artifacts. The experiments revealed that even after exposure over hundreds to thousands of years no silicate corrosion products had been formed even though the concentration of dissolved silicates was high. The evaluation of the kinetics of the corrosion process showed that the original parabolic dependence of corrosion penetration on time changes to a semi-parabolic (linear) dependence over such time periods. The results of the project led to the estimation of the service life of the carbon steel outer casing to 10^4 years, which will be sufficient in view of the fact that the main barrier of the WDP, the inner casing made of stainless steel, will ensure the required lifespan of 10^6 years. The outer casing is required to remain intact over the initial disposal period during which the oxygen present will be fully consumed and the temperature will drop to below 40°C. The time required for suitable conditions to prevail for the inner casing has been estimated at several thousand years under DGR conditions; for example, Kotnour et al. (2016) estimated this period at 2,600 years.

Based on the measurement of the modulus of elasticity, the mechanical properties of the aggregates of corrosion products are evidently very weak, which means that they are easily broken. The ease of deformability and high porosity of corrosion products suggests that concerns that newly-formed corrosion products with volumes greater than the original metal may act to enhance the ambient pressure acting on the WDP are probably unfounded (Stoulil et al. 2022).

This factor was also verified as part of the *Processing of samples from corrosion experiments - Corrosion products 2* project (Stoulil et al. 2023), which involved the analysis of samples from two long-term experiments conducted under underground laboratory conditions and 3 samples from the Kiruna mine where iron ore particles and bentonite were in long-term contact. The analysis revealed no secondary silicate phases with iron cations and nor was there any obvious alteration of the bentonite around the particles. Previous experimental observations of only the marginal and very localised presence of silicate corrosion products after several years of laboratory experimentation (Forman et al. 2021), as well as undeterminable amounts of silicate corrosion products in archaeological analogues after at least several hundred years of exposure (Stoulil et al. 2022), are in no way inconsistent with the samples from Kiruna, which had been exposed for at least millions of years. Thus, (alumino)silicate phases do not need to be taken into account in the WDP lifespan models.

The critical temperature of 40°C for stainless steel was verified as part of the RADMIC project (TAČR, SÚJB guarantor, Stoulil et al. 2024). The critical temperature is that at which enhanced resistance to corrosion is guaranteed in stainless steel. It comprises an important parameter that will affect the project designs of both the WDP and the DGR.

The most significant uncertainty in the process of determining the lifespan of the WDP concerns the initial conditions, including the aerobic environment and the elevated temperature and radiation loads. The WDP must also be designed with regard to its handling in the hot chamber in which it will be necessary to hermetically seal the lid of the loaded SNF WDP.

As part of the *Research and development of a waste disposal package for the deep disposal of spent nuclear fuel up to the sample realisation stage* project (Forman et al. 2021), strength, thermal engineering, subcriticality, shielding and shear calculations (seismicity) were performed aimed at verifying the key parameters of the WDP 440 and WDP 1000. The results were summarised in a report by Matulová et al. (2023). The results of the calculations included:

- To date, the subcriticality calculation has only been performed for WDPs for VVER-440 fuel. The input parameters were selected very conservatively, i.e. fresh fuel with a maximum enrichment of 5.0 wt.% U-235, without a burn-up credit and under emergency conditions following the flooding of the WDP with water (Lovecký, 2020a).

The clean water inside and outside the WDP, the bentonite and the granite rock mass were replaced in the model by so-called moderators following the conservative approach. The calculations revealed that the limit value of the multiplication coefficient is 0.71675; this value meets the legislative limit of 0.95 with a significant reserve of 0.23.

- The WDP shielding requirements are based on safety requirements, especially concerning workers during the operation of the DGR. Three dose equivalent limits were verified. The shielding calculation was performed for both the WDP 440 (Lovecký et al. 2020b) and the WDP 1000 (Gincelová et al. 2020); with regard to VVER-1200 reactors (considered in the shielding calculation as the reference type for new nuclear sources), the fuel will be almost identical; therefore, the results can also be applied to new nuclear sources without any significant changes. According to the calculations, it can be summarised that shielding is achieved with a significant reserve for both types of WDP.
- In order to evaluate the uniform pressure of 20 MPa on the outer and inner casings, the peak values were compared with the limit values set out in KTA standards (already reduced by a safety margin). All the resulting values were below the specified limit values. Concerning the evaluation of uneven pressure, the comparison of the resulting and limit values confirmed that both types of WDP are sufficiently resistant to uneven loading.
- Seismic resistance and the assurance of sealing at the end of the assumed lifespan of the WDP were proved via the basic calculation for proving the ability of WDPs to withstand general design-considered force impacts. In the future, this calculation should be followed by the application of a more precise calculation of the seismic resistance of the WDP, which will take into account the site of the DGR, and the calculation of the resistance of the inner casing
- The thermal calculation proved that the structures of the WDP 440 and WDP 1000 meet the conditions for compliance with the limit temperatures of the fuel cladding and the various components of the WDP, provided that undamaged fuel is disposed of in the DGR, the SNF has been stored for 65 years since the end of irradiation in the reactor in an interim SNF storage facility and meets the residual limits listed above. The thermal conductivity of the considered air gap (0.01 m) should also help to ensure that the temperature of the bentonite does not exceed 95°C.

5.7.1.2 Ongoing and planned work

In terms of subsequent research on the WDP, it will be necessary to confirm via an extensive research programme the corrosion resistance of selected materials in the DGR environment under the various conditions that may occur in the repository over a period of one million years and to specify the conditions of the filling of the disposal well that will surround the WDP.

The testing of the selected materials must be conducted under both laboratory and real environment conditions. It is important that involvement will continue in international projects at the Grimsel underground laboratory and domestic experiments will continue at the Bukov URF under long-term stable conditions that are close to the assumed conditions in the DGR. Particular attention will be devoted to the long-term prediction and modelling of these processes. Long-term experiments will serve to monitor the simultaneous influence of various conditions under which certain processes will be suppressed via their mutual influence, while others will be accelerated. Moreover, the testing will continue of samples from archaeological artifacts and natural analogues, which will provide information on corrosion processes over longer time periods.

The Pilot corrosion experiment (see Appendix 1, SO2020-086) was designed to verify the behaviour of WDP materials under DGR-type conditions. This long-term (10 years) in-situ experiment will also provide the information necessary for the granting of a licence for the proposed WDP design, concerning which it will be necessary to prove that the WDP meets all the specified requirements. The project will determine the corrosion resistance and corrosion rate of the WDP, i.e. two of the most important parameters. The data will also be used in the assessment of the long-term safety of the DGR.

Analytical work will be followed by modelling, which will verify the suitability of the WDP materials studied in the *Mock-up Josef in-situ experiment dismantling project* (see Appendix 1, SO2022-035), in which carbon steel and Czech bentonite materials have been interacting for a period of 10 years. WDP research is also underway as part of the EURAD WP CONCORD (EU programme Grant No. 847593, see Appendix 1) project, which is investigating the influence of temperature, radiation and microbiological activity on the corrosion of carbon steel (S355J2H) and the properties of Czech bentonite (BCV). Modelling research is also underway as part of the EURAD WP ACED (EU programme Grant No. 847593, see Annex 1) project.

The microbially induced corrosion (MIC) of WDP materials is being investigated in the *EURO-MIC* project. Although the topic of microbiologically influenced corrosion in the DGR environment has been underway for many years, most research activities to date have focused on just one group of microorganisms – sulphate reducing bacteria (SRB), the metabolic product of which comprises aggressive sulphane that is responsible for chemical microbially induced corrosion (CMIC), particularly with concern to copper, which is used as the outer cover of the WDP by countries that plan DGRs near to the sea. However, bentonite contains a wide spectrum of microorganisms with different metabolic properties and their role as potential agents of electrochemical microbially induced localised corrosion (EMIC) has not yet been investigated in detail. The project will therefore address the EMIC of a range of microorganisms that occur naturally in bentonite.

The European EURAD 2 programme (due to commence in Q3/2024) - WP InCoMand will include the identification and qualification of new materials for the construction of WDPs for high-level waste (which includes spent nuclear fuel) and also aims to enhance the knowledge of the behaviour of traditional and new materials over the long term under the most realistic DGR conditions possible. Researchers will investigate how, whether and to what extent the formation of corrosion products will impact microbial activity under DGR conditions. The study of the synergistic impact of corrosion attack and mechanical loading on the potential failure of WDPs remains a topic for investigation with concern to most DGR concepts. The project will include the investigation of the impacts of changes in the volume between the original metal and its corrosion products on the swelling pressure of the bentonite and, subsequently, on the total load.

The functionality and reliability of the two-layer WDP design (SO2021-053-04, Appendix 1) are currently being verified as part of the overall assessment of the DGR concept (see chapter 5.11.2.2).

It will be necessary to focus primarily in the upcoming period on:

1) the updating of the requirements for the WDP (will be included in the summary of requirements processed within the requirements management system),
2) the identification and evaluation of possible alternative types of WDP as proposed in foreign programmes (Sweden, Finland, Belgium, etc.),
3) the ongoing evaluation of currently available analysis and laboratory and *in-situ* experiments,

The outputs required for fulfilling the above-mentioned objectives are listed below, accompanied by an indicative schedule:

- to create a database of corrosion experiment data. The summarisation of the experiments conducted to date, including the conditions under which they were conducted and the results. The analysis of the experiments conducted and the design of a set of experiments that will serve to verify and/or supplement the conclusions drawn from previously completed projects,
- to supplement the subcriticality calculation for the WDP 1000 and the strength calculation of the impacts of uneven pressure for the inner casings of both WDPs,
- to prepare, commence and continue experiments at the Bukov URF on selected material samples including carbon steel, stainless steel and, for comparison, copper (as used in the Swedish and Finnish concepts).
- to design and computationally verify the WDP backup solution (only in the event that it is not be possible to demonstrate the sufficient resistance of the reference design).

Tab. 14 Estimated schedule of activities planned up to 2028 concerning the design of the WDP for SNF; indicative schedule showing continuity (outputs to) with key SÚRAO activities according to Tab. 1 in the right-hand column

Activity	FROM	TO	Outputs to
Summarisation and analysis of data from corrosion experiments and the proposal of other necessary research	2024	2025	10
Supplementing of calculations for the WDP 1000	2023	2025	10
Design, preparation and initiation of verification experiments under laboratory conditions and at the Bukov URF	2025	2028	10

5.7.1.3 Future work

During the development of the WDP and the analysis of the various proposed concepts, it is necessary to take into account the latest data on the SNF, the condition of the storage containers, the plans of the SNF generator (ČEZ) for dealing with damaged fuel assemblies, the period of SNF storage and planned new nuclear sources. Throughout the development of the WDP, cooperation with the nuclear power plant operator is essential, as is the verification of real data and reacting to changes in a timely manner.

The development of the WDP must also consider the handling approach. Due to the extent of the DGR and the geometric layout of the disposal spaces, it is expected that the handling of the WDPs will proceed in several phases. Particular attention will be devoted to handling in the hot chamber.

Research will also focus on the automation of systems and the various levels of the inspection of the functionality and safety of the processes involved.

The technological equipment required for the other engineered barriers will depend on the materials finally selected and the approach to the storage and installation of the individual barrier components. This will involve the use of existing technological equipment, their potential modification and, possibly, the automation of selected activities. Development will also include the preparation of related management and control systems and procedures concerning operational verification and functionality testing.

The future objectives of WDP-related research and development are as follows:

- to focus research activities on the preparation of documentation for WDP licencing,
- to propose a method for the handling of WDPs including the technologies used for the transportation of WDPs to the DGR and within the DGR,
- to ensure continuous close cooperation with the nuclear power plant operator. The planned handling of the SNF in the DGR is based on the documentation of, and the strategies applied by, the nuclear power plant operator. The thermo-technical calculations, determination of the resource element and, for example, handling in the hot chamber must respond to the actual storage time of the SNF and its burn-up, and the approach to handling damaged fuel assemblies, i.e. whether they will be sent for reprocessing or will be housed in their own special WDPs,
- the optimisation of the WDP technical design based on the outputs of ongoing projects (e.g. see Appendix No. 1 SO2021-053) and
- the conducting of laboratory tests that imitate the real conditions at the final site.

5.7.2 Waste disposal package for HLW

According to records on RAW (Touš et al. 2018; Pospíšková et al. 2022), the following high-level waste will be disposed of in the DGR:

- Unprocessed SNF from the LVR-15 reactor,
- RAW from the reprocessing of SNF from the LVR-15 reactor (in cylindrical canisters)

The operation of the LR-0 (Research Centre Řež, s.r.o.), VR-1 and VR-2 (ČVUT FJFI) research reactors does not generate spent nuclear fuel due to their low thermal output and limited operating times; only slightly irradiated materials are generated, which will probably be recycled (used for the production of new fuel) following the end of operation of the reactors. More highly enriched fuel that was transported to the Russian Federation for reprocessing, will be returned to the Czech Republic in around 2028 and 2033 (two batches).

According to a report by Pospíšková et al., the WP for unprocessed SNF from the LVR-15 (2022) reactor will correspond to that for SNF (Forman et al. 2021) since the WP requirements will be similar due to the characteristics of the stored SNF. However, the design of the WP must meet the conditions for ensuring nuclear safety (ensuring subcriticality) and respect the dimensions of the fuel assemblies. A disposal WP will also be required for less enriched fuel.

5.7.2.1 Work performed

Following a certain period of time in the wet storage facility (pool), SNF will be transferred to ŠKODA VPVR/M storage and transport WPs in which it will be stored for the required time at the HLW storage facility at ÚJV Řež, a.s. (two WPs were delivered in 2020 and 2022). This storage method prevents the occurrence of damage to the fuel cladding, which occurred on rare occasions in the past during wet storage. Although the HLW storage facility has 2 cooling pools (permitted capacity 450 fuel assemblies, technological capacity up to 900) their use is not expected. A sufficient number of ŠKODA VPVR/M WPs are available for storage (the required capacity will be 11 WPs) (Podlaha and Trtílek 2023a).

5.7.2.2 Ongoing and planned work

Development in the upcoming period will focus primarily on the following activities; a preliminary schedule is shown in Tab. 15:

1) the identification of the requirements for the WDPs for vitrified waste and SNF from the LVR-15 reactor in the form of acceptance conditions for DGR disposal, and
2) the initiation of the development of a modified WDP for vitrified waste and SNF from the LVR-15 reactor.

Tab. 15 Estimated schedule of activities planned up to 2028 concerning the design of the WP for other HLW; indicative schedule showing continuity (outputs to) with key SÚRAO activities according to Tab. 1 in the right-hand column

Activity	FROM	TO	Outputs to
The identification of the requirements for the WDPs for vitrified waste and SNF from the LVR-15 reactor in the form of acceptance conditions for DGR disposal,	2024	2025	10
The initiation of the development of a modified WDP for vitrified waste and SNF from the LVR-15 reactor	2025	2028	10

5.7.2.3 Future work

Future work in cooperation with waste generators and the SÚJB will comprise:

1) the updating of research studies for mapping the approach to the disposal of HLW in other countries, particularly EU states. It will be necessary to include the form of the WDP and the design of the repository, its construction and the waste handling method,
2) the initiation of the HLW WDP licencing process.

5.7.3 Waste disposal package for ILW

According to records on RAW (Touš et al. 2018 and Pospíšková et al. 2022), intermediate-level waste, which is unacceptable for disposal in near-surface repositories and will, therefore, be disposed of in the DGR, occurs in several forms:

- RAW in drums with a volume of 216 l,
- Fuel from other research reactors (VR-1, VR-2 and LR-0),
- Lump RAW of various sizes.

ILW, especially from the decommissioning of nuclear power plants, will be disposed of in a separate part of the DGR designated for this type of RAW, i.e. separated from the SNF section, in approved WPs. The development of WPs for LLW and ILW, which is unacceptable for disposal in near-surface repositories, requires close cooperation with the waste generators. SÚRAO will be required to determine the conditions for the acceptability of these WPs in the DGR.

5.7.3.1 Work performed

A concrete WP for ILW was proposed in the 1999 reference project (Holub et al. 1999). The concrete container (see Fig. 11) was designed with an outer and inner walls of 10 mm thick steel sheets with a welded inner and outer bottom of a thickness of 15 mm. The two walls are welded to an upper flange ring in the upper part of the WP. The space between the inner and outer walls is filled with concrete. The WP will be covered by a bolt-on lid made of the same steel material as the flange ring. The outer bottom of the WP features rectangular longitudinal openings for the transport of the WPs in the DGR corridors. The surface of the concrete container is coated with ZnAl (Holub et al. 1999).

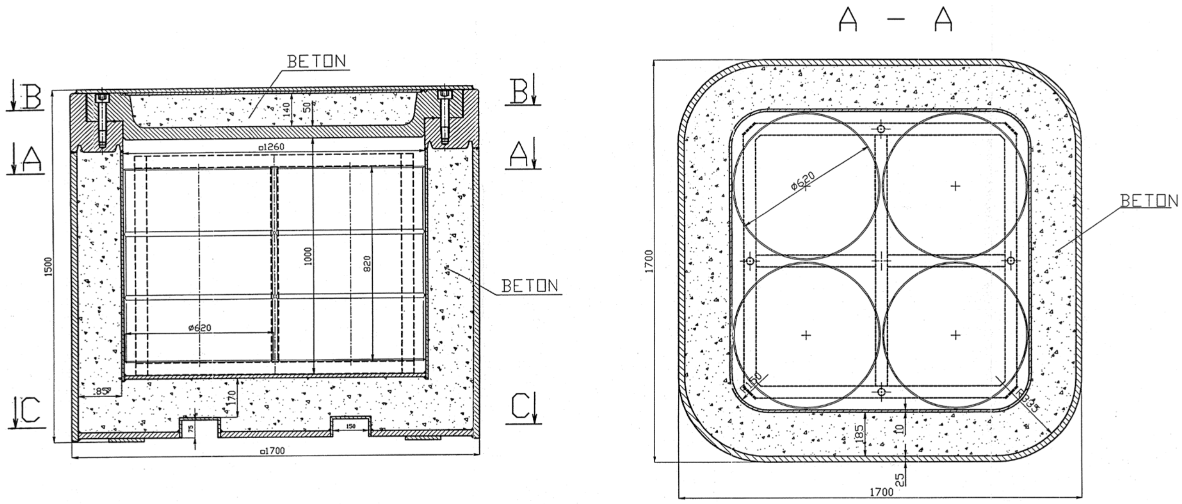

Fig. 11 Drawing of a concrete container and the positioning of 4 drums with RAW

The currently considered approach to the disposal of ILW in WPs is described in a report by Pospíšková et al. (2022), which was compiled as part of the *Research and development of a WP for HLW and ILW project*.

The WP for waste containing long-term radionuclides will differ (in terms of its dimensions, including the wall thickness) according to the form of RAW, i.e. according to whether the WP will comprise the primary container into which the RAW will be emplaced directly (from dismantling and demolition) or will serve for the repackaging of primary containers (the drums in which the RAW is currently stored at the Richard repository).

The project included a proposal for WPs for RAW that is stored in drums. Cube-shaped WPs allow for the emplacement of up to 4 drums or 2 steel drums with a volume of 216 l (Fig. 12).

The WP for four 216 l drums has basic internal dimensions of 1.3 x 1.3 x 1.0 m (W x L x H) and each 216 l steel drum has a diameter of 595 mm and a height of 880 mm.

- Internal volume: 1.69 m^3
- Filling of the internal space in the WP: cement mixture
- 4 suspension screws positioned in the cover of the WP for handling purposes
- A slot located in the bottom part for the forklift truck handling of the WP.

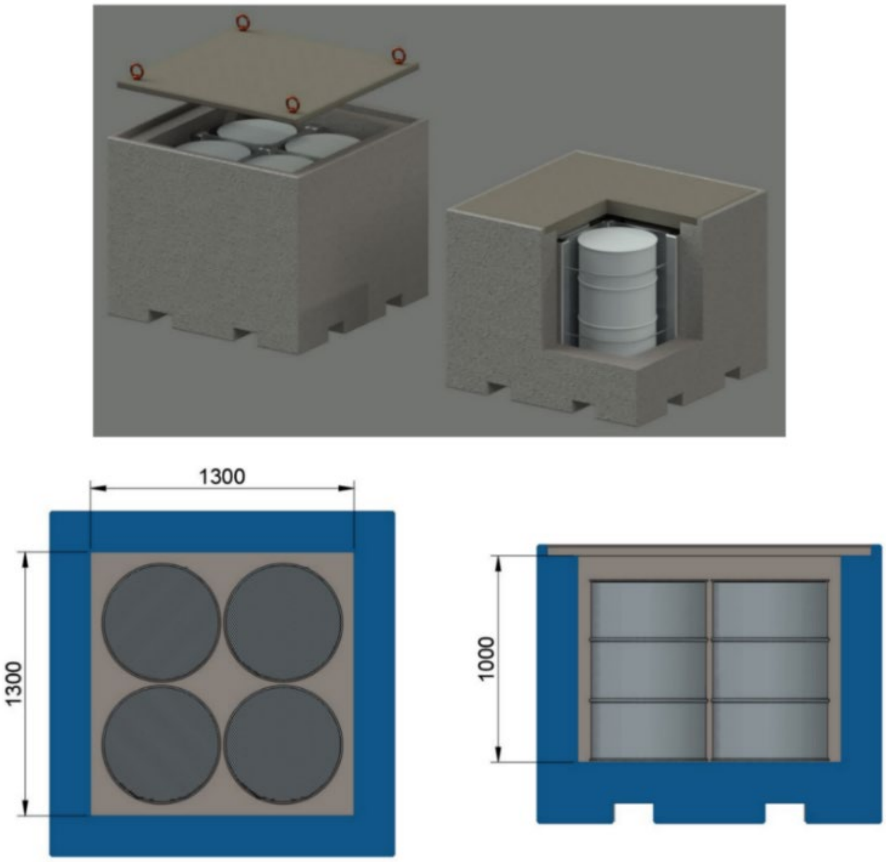

Fig. 12 Conceptual design of the WP for 4 drums of RAW (Pospíšková et al. 2022)

WPs have also been designed for lump RAW of various sizes; the design of the largest type is shown in Fig. 13. The maximum recommended outer size is 2.4 x 2.2 x 2.0 m (W x L x H) due to the requirement for the handling of the WP in the limited spaces of the DGR mine workings; the filled WP will weigh approx. 10 t. Depending on the RAW content, the WP dimensions can be adapted to the requirements of the contracting authority.

- Total volume: 10.56 m^3
- Filling of the internal space in the WP: according to the nature of the RAW
- 4 suspension screws positioned in the cover of the WP for handling purposes
- A slot located in the bottom part for the forklift truck handling of the WP.

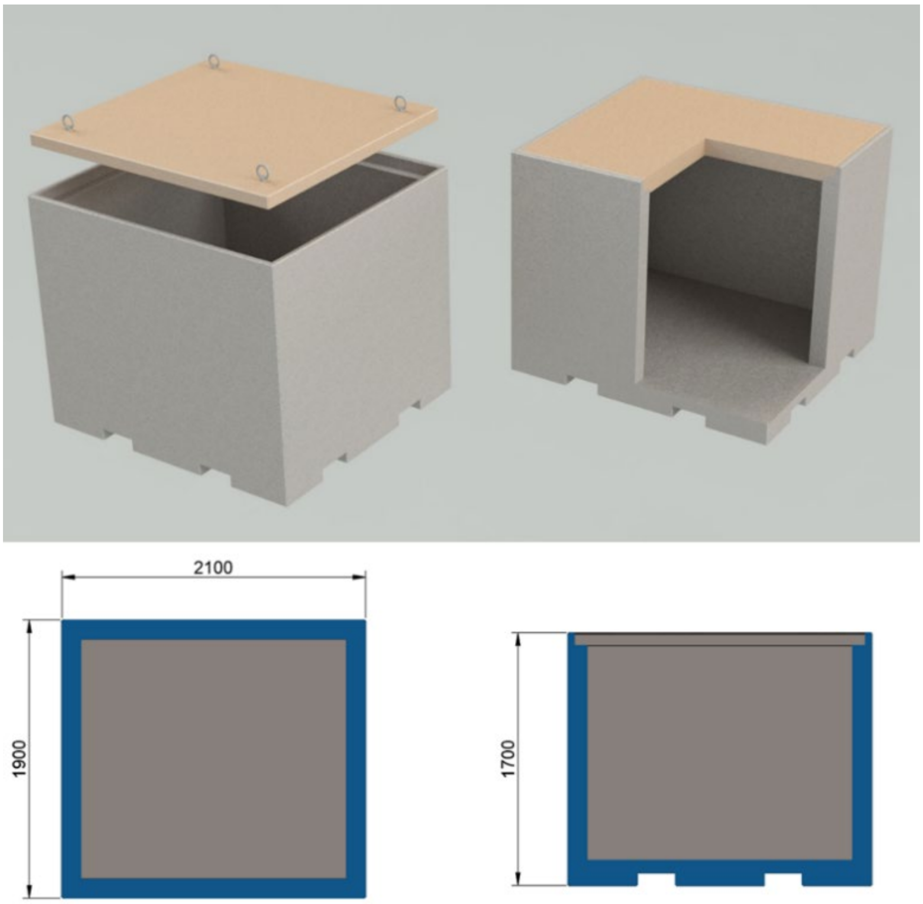

Fig. 13 Conceptual design of the WP for lump RAW; largest variant (Pospíšková et al. 2022)

The thickness of the walls of the WPs will be determined according to the expected waste inventory, the materials used and the required mechanical resistance (requirements set out in Decree no. 379/2016 Coll.). The choice of the WP materials must respect the requirements placed on the WP – its lifespan, which is, again, related to the expected waste inventory. However, experience suggests the use of steel and cast iron or concrete or fibre concrete, although it is probable that it will be made from a combination of materials - a metal container with the emplacement of a concrete container.

WPs for ILW can either be purchased in the market or be designed in-house. The European market would be ideal in this case due mainly to harmonised licencing requirements, which make it easier for companies to enter the market and reduces the administrative burden.

5.7.3.2 Ongoing and planned work

Following the conducting of studies as part of the *Reference project and the update thereof* (Holub et al. 1999; Pospíšková et al. 2011), the main priority was to suggest a comprehensive concept for the disposal of other RAW in the DGR fully taking into account current knowledge and developments in the field of RAW disposal. The research and development of WPs for HLW and ILW was described in detail as part of the *Research and development of WPs for HLW and ILW* project. It was concluded that a wide range of WPs are already available in the Czech and European markets that are able to satisfy the requirements for the disposal of ILW in the Czech Republic. Thus, it will be necessary to evaluate the advantages and disadvantages of implementing an in-house development programme versus the use of existing WPs.

5.7.3.3 Future work

In the case of a decision to develop an in-house WP for ILW, samples of candidate materials for the WP should be subjected to controlled ageing under laboratory and, subsequently, in-situ conditions. The research should focus on material interactions and the potential development of gases inside the WP. In the case of a decision to purchase WPs, it will be necessary to constantly monitor the development of the WP market in the Czech Republic and abroad.

Development in the upcoming period will focus primarily on:

1) the updating of the research study for the mapping of the approach to the disposal of other RAW in other countries with special emphasis on EU states. It will be necessary to include the form of the WP and the disposal approach, the construction of the WP and the waste handling method,
2) the selection of potential types of WP in cooperation with waste generators.

5.8 Filling of the disposal wells, tunnels and chambers

The filling of the disposal well comprises an engineered barrier that has both a damping and sealing function (buffer). The filling (backfill) of the disposal tunnels is also one of the most important safety components of the DGR.

The buffer primarily prevents the contact of the WDP, which fulfils the primary safety function in the DGR (category II safety function according to section 8 para. 1 of Decree No. 329/2017 Coll.), with the water and corrosion-active substances present in the rock environment (chlorides, sulphides) so that, under normal DGR development conditions, both groundwater and corrosion-supporting substances reach the WDP only via (very slow) diffusion. Moreover, the high density of the buffer largely prevents the activity of microbes and thus limits the microbial corrosion of the WDP.

The main function of the backfilling of the disposal tunnels is to prevent the movement of the buffer so that it maintains its safety functions.

The other safety functions of the disposal well buffer and the disposal tunnel backfilling can be summarised as follows:

- to contribute to the low mobility of radionuclides so that radionuclides released from the WDP following damage thereto migrate only very slowly into the rock environment,
- to ensure, in tandem with the disposal layout in, and the sufficient depth of, the DGR, the dispersion of heat from the WDP,
- to ensure the removal of generated gases,
- to ensure the mechanical stability of the WDP and, thus, the DGR disposal system.

Bentonite was proposed as the buffer material in the Swedish KBS-3 concept. Due to its unique properties (geomechanical and chemical), bentonite will expand to fill the so-called technological joints and efficiently seal the disposal site (Savage et al. 1999). This material was also adopted for the Czech disposal concept and has been considered in the Czech reference project since 1999 (Holub et al., 1999). The currently assumed technical approach is described in SÚRAO report TZ 711/2023 (Hausmannová et al., 2023).

The backfilling of the SNF disposal tunnels will not be in direct contact with the WDPs; however, it will be in direct contact with the buffer. Bentonite has also been proposed as the reference material for this DGR structural component.

The material to be used for the backfilling of the ILW disposal chambers is currently in the development stage in the Czech Republic. Foreign disposal concepts (SKB, SFL) are considering two types of material, i.e. cement for the disposal of metal materials from the decommissioning of nuclear power plants and bentonite for the disposal of other waste.

In 2002-2006, Czech bentonites and smectite-rich clays were characterised as part of the Verification of the Substitution of Bentonites by Montmorillonitic Clays (Carlson,L. & Keto,P. 2006) project aimed at determining whether they could be used as buffer and backfill materials in the DGR. The characterisation included mineralogical, chemical and geotechnical investigations, and thermal stability and sorption experiments, and was carried out independently in the Czech Republic, Sweden and Finland. The conclusion of the project was that while Czech bentonite clay deposits are relatively heterogeneous, they contain relatively high amounts of swelling minerals; therefore, Czech bentonites can be considered as buffering and backfill materials for the purposes of the Czech deep geological repository.

5.8.1 Work performed

Up to the present, most of the work in this area has focused on bentonite and its use for buffer and backfill purposes; the fillings of the disposal chambers were addressed only to a marginal extent. Therefore, the text in this chapter summarises only the work that focused on the buffer and backfill.

Research into filling materials for the DGR has been ongoing at SÚRAO since 1999 and assumes primarily the use of Czech bentonites. Data and information is available on this topic from more than 40 projects and expert reports that have focused on the characterisation of Czech bentonites (its geochemical, geotechnical and mineralogical parameters) as well as its development following loading (thermal, radiation, contact with other materials). Research began via the conducting of isolated national projects and was later expanded to include international cooperation. From small-scale experiments conducted under laboratory conditions, the research moved on to include experiments in real rock mass environments in underground laboratories (the Josef URC and Bukov URF in the Czech Republic, the Grimsel Test Site in Switzerland). The requirements for these engineered barriers have been defined to date in the Czech concept only in general terms (as adopted from SKB and Posiva requirements – Posiva SKB Report 01, 2017). The numerical parameters and specific values for the safety assessment of bentonite materials remain the subject of intensive research and development (Hausmannová et al. 2018).

Previously completed experiments were aimed at the selection and description of clay raw materials suitable for use in the DGR (bentonite and montmorillonite clays of Czech origin) and their behaviour under DGR conditions. The data collected to date on Czech bentonites was summarised and analysed in a report by Šachlová et al. (2022), the main aim of which was to assess the suitability and stability of Czech bentonites for the purposes of the DGR over both the short and long terms. The assessment process will require further data going forward, concerning which a specific experimental programme has been compiled (Svoboda et al. 2023). The supplementing of existing data will make a valuable contribution to enhancing the understanding of the stability of Czech bentonites and, thus, to the assessment of their suitability for use as the filling material in the DGR. Up to the time this data is obtained, SÚRAO will continue work on the overall project design proposal and the long-term safety assessment in tandem with the preliminary design of the bentonite barriers. This proposal is described in detail in a SÚRAO report by Svoboda et al. (2022).

The main conclusions of the report by Šachlová et al. (2022) regarding the properties and stability of Czech bentonites were as follows:

- The specific characteristics of Czech bentonites comprise:
    1. the high content and variability of non-smectite minerals (kaolinite, illite, carbonates, Fe-oxyhydroxides, feldspar, quartz)
    2. Ca-Mg type smectite containing Fe^{3+}.
- The content of non-smectite minerals together with amorphous phases makes up 30-40 wt.% of the bentonite. These mineralogical properties are manifested by a high content of Fe_2O_3, CaO and Ctot. Compared to foreign bentonites, Czech bentonites have a lower cation exchange capacity, total specific surface area, swell index and swelling pressure, and higher hydraulic conductivity.
- The long-term stability of bentonite provides for its resistance to chemical, mineralogical and mechanical changes caused by external influences. The evaluation of the stability of bentonite revealed its differing behaviour under thermal stress in dry and saturated conditions. The thermal loading of bentonite under dry conditions leads to the deterioration of its parameters, whereas the thermal loading of water-saturated bentonite leads to the enhancement of certain parameters upon the initiation of the loading process followed by a return to the original values or even the deterioration of the parameters after 2 or more years of loading. The enrichment of the K+ solution in combination with enhanced temperatures may lead to the illitisation of smectite.
- The influence of radiation on the geochemical and geotechnical properties of bentonite has not yet been investigated.
- Loading due to contact with powdered iron or steel leads to the significant deterioration of the geochemical parameters. It is not yet clear at what distance from the steel the bentonite is affected. In most cases, corrosion products have been mapped only in the layer adjacent to the steel. The presence of powdered iron has been proven to increase the microbial activity and especially the activity of sulphate-reducing bacteria (SRB).
- A further factor that influences the stability of bentonite concerns the salinity of the groundwater, which, if it reaches elevated values in combination with the Na/Ca character of the water, leads to the transformation of montmorillonite into kaolinite and pyrophyllite. The interaction of bentonite with saline water also results in a decrease in the swelling pressure. However, the salinity of the groundwater in the Czech Republic is low; therefore, the stability of Czech bentonite should not be negatively affected by interaction with the groundwater.
- One of the main requirements concerning the buffer and the backfill comprises impermeability to water and corrosion-causing substances; hydraulic conductivity < 10^{-12} m/s and swelling pressure > 1 MPa. Of the geochemical-mineralogical properties,

the main criteria consist of the sorption and retardation properties, the total sulphide content (< 0.5 wt. %), the total sulphur content including sulphidic sulphur (< 1 wt. %) and the total content of organic carbon (< 1 wt. %). These criteria are based on Posiva-SKB (2017). SÚRAO plans to perform its own design analysis and to determine the safety indicators/criteria and their values related to filling and sealing materials in the near future.

- The influence of microbial activity on the stability of bentonite continues to be the subject of research both internationally and in the Czech Republic. Czech studies include the observation of microbiologically loaded bentonite, changes in the behaviour and appearance of bentonite, decreases in the swell index, changes in the CEC and the representation of exchangeable cations. This approach is in accordance with foreign research outputs concerning the observation of geochemical changes in bentonite as a result of the action of microorganisms.

The BioBen report (Černá, Šachlová et al. 2023) set out the values of the physical factors that significantly limit the survival and proliferation of microorganisms that occur naturally in deep underground water and bentonite, i.e. primarily with concern to the pressure, temperature, ionising radiation, water and nutrients. The main conclusions of the report were as follows:

- The reduction of microbiological activity is influenced by the reduction of pore spaces, reduced water activity and the limitation of nutrient diffusion.
- With concern to samples of fully saturated bentonite with a dry density of approx. 1600 kg/m^3, microbial activity is significantly suppressed during all types of incubation.
- A temperature of 90°C was identified as the limit for microbial activity and survival for both compacted bentonite and bentonite suspension samples in a fully saturated environment.
- Microorganisms survive a lack of water in the dormant state.
- Irradiation with low doses of gamma radiation is unlikely to represent a limiting factor in terms of the development of microbial activity in the DGR RAW environment (tested at a dose rate of 0.1 Gy/h over 18 months).
- The contribution of internal nutrients originating from the non-clay mineral phases of bentonite pore water provides a sufficient source of nutrients for the development of microbial activity.

The discovery that microorganisms that originate from saturation media are not significantly reflected in the detected microbial composition of bentonite either in the suspension or compacted forms is significant and suggests that the influence of the microbiological composition of groundwater will probably be low in terms of microbiological development in the DGR. This factor has been reported in both Czech and foreign studies.

To date, only two projects that focus on the research of backfill materials have been completed (2007–2012): *Sprayed filling technology* and *Research into the potential for the use of sprayed bentonite for the construction of the sealing layer of the DGR*. The two projects served to verify the use of sprayed bentonite technology; however, the technology will have to be optimised for use at the real scale.

Research has also been conducted on the potential for the production of bentonite pellets from Czech bentonites (Fig. 14). The *Pellets project* (2017–2020) successfully led to the production of a mixture of bentonite pellets at the pilot and industrial scales with a dry density of the single bentonite pellets of over 2000 kg/m³ for use in the DGR. The corresponding average dry density is 1400 kg/m³ and the swelling pressure around 2.5 MPa. Other successfully completed projects include the creation of a bentonite testing methodology for determining the geochemical, geotechnical and mineralogical parameters (Vašíček et al., 2022) and the creation of a database of Czech bentonites.

Fig. 14 Bentonite pellets from the final compression tests (Pacovský et al. 2018)

5.8.2 Ongoing and planned work

Further related research activities are planned for the period up to 2028, a list of which and an indicative schedule are provided in Tab. 16. Subsequent research in this period will be planned according to the outputs achieved.

Tab. 16 Estimated schedule of the key activities concerning the proposal of the filling materials for the disposal wells, corridors and chambers for ILW; indicative schedule showing continuity (outputs to) with key SÚRAO activities according to Tab. 1 in the right-hand column

Activity	FROM	TO	Outputs to
Additional research aimed at the evaluation of the stability and suitability of Czech bentonites	2022	2026	10
Selection of the filling materials	2024	2025	10
Updating of the technical design of the buffer, backfill and disposal chamber filling materials for ILW	2026	2026	10

5.8.2.1 Filling of the SNF disposal wells and tunnels

The research and development of bentonite barriers in the upcoming period will focus on the following topics:

- Supplementary work aimed at evaluating the stability and suitability of Czech bentonites and their comparison with selected foreign materials (material interactions, microbiological interactions, gas permeability, radiation and thermal loading, transport of radionuclides)
- The determination of the montmorillonite content as a parameter that limits the suitability of bentonite in the DGR
- Issues surrounding erosion; chemical and mechanical
- Geochemical and mineralogical stability (changes in the carbonate cycle, transformation of goethite, SiO_2 gels and the potential for the formation of Fe(Al)SiOx phases)
- The influence of microorganisms on the stability of the bentonite
- Forming an understanding of the thermal relaxation element of bentonite (a phenomenon recently observed in experimental research carried out within the EURAD WP HITEC programme, where an unexpected decrease in the swelling pressure of the bentonite occurred during heating).
- Issues surrounding earthquakes; bentonite shear parameters
- The updating of the technical design of the barriers based on new findings (compressed blocks, pellets or combinations)
- Forming an understanding of the compatibility of construction materials with bentonite barriers
- The assessment of the heterogeneity of bentonite components

In order to fulfil these objectives, the analysis will be performed of ongoing experiments, both domestic and foreign:

- Mock-Up Josef Dismantling (see Appendix 1, SO2022-035),
- Pilot corrosion experiment in the Bukov URF (see Appendix 1, SO2020-086),
- Interactive in-situ physical models in the Bukov URF (see Appendix 1, SO2017-053),
- Fillings and other engineered components of the DGR (see Appendix 1, SO2020-092),
- Engineered barrier 200°C (see Appendix 1, SO2018-002),
- DOPAS – EPSP (see Annex 1, SO2020-032),
- HotBent (see Appendix 1, SO2019-004),
- COST EUROMIC (see Appendix 1),
- EURAD CONCORD (see Annex 1, EU programme Grant No. 847593),
- EURAD HITEC (see Appendix 1, EU programme Grant No. 847593) and
- EURAD GAS (see Annex 1, EU programme Grant No. 847593).

5.8.2.2 Filling of the ILW disposal chambers

The research of the issue of the filling of the disposal silos or chambers for ILW is currently underway. The outputs from the safety assessment of the Richard repository and the safety instructions issued by the SÚJB will be important in terms of the final design proposal.

The use of concrete or Czech bentonites is assumed (Svoboda et al. 2022). The RAW disposal horizon has not yet been precisely determined. It will be possible to use high pH-type concretes provided that the interaction of the concrete leachates with the bentonite used in the SNF repository is minimised due to its separate location. It will be possible to base the concrete material on the parameters of the concrete used to stabilise the chambers at the Richard repository. The suitability of this concrete was verified via the CORI (Cement-Organic-Radionuclide-Interactions) WP of the EURAD programme (EU Grant No. 847593). The results will be published in technical report TZ 733/2024.

If the concrete filling material is based on that used at the Richard repository, the composition of the concrete will be modified for the specific conditions prevailing at the DGR site, especially with regard to the chemical composition of the local groundwater.

In connection with the planned development of the ILW disposal system in the DGR, it is now necessary to:

- define in more detail the requirements for the filling of the ILW disposal spaces, especially with regard to the time required for the safe disposal of the waste,
- study alternative filling materials for the ILW section (e.g. a geopolymer matrix),
- select the most suitable filling material.

5.8.3 Future work

Following the selection of the final site, the rock mass and water parameters of the disposal horizon will already have been determined. The next stage will involve the testing of the barriers under local conditions, in particular the testing of the interaction of the bentonite and, possibly, concrete with the groundwater.

Moreover, it will be necessary to verify the proposed barriers at the real scale in a real rock mass environment, for the purpose of which real-scale and demonstration experiments are planned at the Bukov URF (see chapter 5.12). In addition, it will be necessary to prepare the technical design solution for the filling process based on the form of the disposal spaces (chambers, silos) and the materials used (concrete, bentonite blocks/pellets).

Other work will include the development and optimisation of the production of the various components and the manufacturing and handling methods and techniques.

5.9 Other DGR engineered components (filling materials, plugs, injection materials and other structural elements)

The filling systems of the disposal wells and tunnels will need to be supplemented by a range of other engineered components that will have different functions depending on the respective requirements and their locations. Although these components will not serve as primary physical safety barriers, their interaction with the primary barriers could affect the safety functions thereof but only if they will be left underground following DGR closure. Currently, the plan is to leave these structures on site.

The design of the tunnel plugs will be particularly important; these plugs will serve to separate the already filled parts of the repository from the operational spaces and provide a safe sealing function. The fillings of the other areas of the DGR (corridors, boreholes, service areas, etc.) will also be important in terms of their potential to form preferential pathways for the migration of radionuclides. The research and development of the other engineered filling components and seals will primarily be addressed in connection with the repository closure process.

Concerning the future construction of the DGR, it is necessary to address the issue of specific structural materials (concrete) and elements thereof (e.g. reinforcement and grouting). This will concern mainly the reinforcement of the disposal areas with cement-based materials that must meet strict requirements concerning both their chemical and mechanical properties and potential interactions with the other materials used in the DGR.

The approach to the issue of the structural systems of the DGR, which has been under consideration in the Czech Republic since 1999 (Holub et al. 1999; Pospíšková et al. 2011), is primarily based on experience in the field of underground construction.

The construction of the DGR will include the use of steel anchors and cement materials for a range of structural components, e.g. sprayed concrete (shotcrete) for the primary lining, the concreting of the floors and grouting materials for sealing purposes.

5.9.1 Work performed

Issues related to "other" engineered components have been addressed in a number of projects to date on the construction of plugs and the research of suitable materials and the study of their long-term behaviour and interactions.

Most of the research has focused on the development and subsequent study of concretes with reduced pH, the use of which is assumed as the construction material for e.g. the stabilisation of the corridors and sealing plugs. The main advantage is that, thanks to the reduced pH, the concrete will not negatively impact the behaviour of the bentonite, which will fulfil a fundamental safety function in the DGR. In 2019, SÚRAO developed a concrete material with reduced pH (Pernicová et al. 2019). Specimens of the material are being tested on an ongoing basis at the Bukov URF aimed at verifying the stability of their mechanical properties when exposed to underground conditions (high humidity). The interim test results indicated increasing compressive strength over time and a slightly decreasing pH trend (Čítek et al. 2020). Concrete samples with a reduced pH content were tested in the EURAD MAGIC programme (EU project Grant No. 847593); one of the interaction tests involved the study of the mutual reaction of the concrete material and a suspension of Czech BCV bentonite. The programme is currently in the final stages and the preparation of final reports is underway. The results are expected to prove the stability of the concrete required for the structural components of the DGR.

In addition to cast iron reinforced concrete, sprayed concrete (shotcrete) will also be used to stabilise the underground corridors. The reinforced concrete mixture was adapted for use in the dry spraying method in terms of the size of the aggregate content and without the use of a plasticiser, defoamer or accelerator. Test spraying has been performed in the underground complex of the Bukov URF. The properties of the sprayed concrete mixture fulfil the requirements for its use and it is being used experimentally in the construction of new mine workings in the Bukov URF.

The EPSP experimental plug construction project also focused on the structural elements of the DGR (see Svoboda et al. 2015). The aim of the experiment was to verify the functionality of the design of the plug and the suitability of both the materials and the technological approach for use in the DGR. The plug system consists of three main parts - an inner plug made of pH-reduced fibre reinforced concrete, a bentonite core (seal) and an outer pH-reduced fibre reinforced concrete plug. The plug is being subjected to water (air or bentonite suspension) pressure from a pressure chamber located behind the inner plug. In addition to the behaviour of the experimental plug itself, the response of the surrounding rock mass is being monitored using measuring bolts installed in boreholes drilled in the vicinity of the experiment. The experimental plug is successfully fulfilling its intended sealing function. The project will be concluded in 2024 with the dismantling of the plug and the documentation of its overall condition.

A further important project comprises the Interaction Experiment as part of which physical models have been installed in the Bukov URF. The objective is to verify the properties of the bentonite sealing layer as affected by the presence of the rock environment and groundwater, and the interaction with cement materials at elevated and non-elevated temperatures. The experiment consists of five non-heated and five heated physical models (four models heated with electric heaters to 100°C and one to 200°C). The loading (heating and saturation with water) and monitoring phases of the experiment commenced in March 2019 and will run until 2024. The monitoring of the various parameters has revealed the long-term stabilisation of the measured parameters. The interim results of the experiment are provided in the Interaction Experiment No. 6 report (Svoboda et al. 2023). The first stage of the modelling served as support for the locations of the physical models in the laboratory testing chamber and consisted of models of the propagation of heat around the physical models. The second phase involved the creation of a predictive THM (thermo-hydro-mechanical) model of the behaviour of the individual physical models. The final modelling phase involved the validation of the models against the measured data and serves for the interpretation of the behaviour of the experiment (Krejčí et al. 2020).

5.9.2 Ongoing and planned work

The aim of the research and development in this area concerns primarily the study of the stability of materials under DGR conditions via the conducting of experiments in the Bukov URF (see chapter 5.12.2). The experiments will focus on the influence of the interaction of bentonite with the other construction materials (Portland cement (OPC), reduced pH leachate concrete (LPC), metal reinforcement materials, grouting materials) that are expected to be used in the DGR (Večerník et al. 2022 ; Svoboda et al. 2022) under real conditions. Details of the various planned experiments are provided in technical report TZ 684/2023 (Svoboda et al. 2023).

Concerning the research and development of other engineered components, the following activities will need to be completed in the upcoming period up to 2028, see Tab. 17.

Tab. 17 Estimated schedule of the key activities planned up to 2028 concerning the proposal of the other engineered components of the DGR; indicative schedule showing continuity (outputs to) with key SÚRAO activities according to Tab. 1 in the right-hand column

Activity	FROM	TO	Outputs to
Evaluation of the stability and suitability of SÚRAO_LPC (reduced pH concrete)	2024	2028	10
Updating of the technical design solution for all the other engineered components of the DGR	2026	2026	10
Dismantling of the EPSP experiment	2025	2027	10

5.9.3 Future work

Future research will include:

- in the long term: the incorporation of the plug system into the DGR project design solution taking into account the specific types of plugs and their functions,
- concerning cement materials: the suitability of the materials that are selected for the DGR (construction materials, engineered barrier materials and matrices for selected types of RAW) for the respective locations must be verified taking into account e.g. the composition of the groundwater at the selected site,
- the verification of the suitability of the other engineered components (e.g. the injection materials) for the selected site,
- the demonstration of the technical feasibility and functionality of the various components of the disposal system via an experimental model based on the vertical WDP disposal concept to be installed at the Bukov URF. A disposal corridor will be sealed with a concrete plug as part of the experiment.

5.10 Operational safety assessment

Operational safety, i.e. both classical and radiation safety, makes up an integral part of the research and development of technologies for, and the transport and handling of, SNF and HLW and the design of the WDPs/WPs. Operational safety and compliance with relevant regulations must be ensured regardless of the selected site in accordance with legislative requirements (Act No. 263/2016 Coll. Atomic Law, Decree No. 422/2016 Coll. on radiation protection and the security of radionuclide sources). The safety analysis of the various research activities will have to be conducted in parallel with the development of the respective components so that the results of the safety analysis can be retroactively included in the technical design solution. The DGR project is specific in that its continued construction and the disposal of RAW will take place simultaneously in the DGR disposal horizon. This requirement must be satisfied based both on the approach to the safety assessment itself and the technical and organisational measures subsequently implemented.

The safety assessment must cover both normal operation and those aspects of the project that could potentially exert significant impacts on the environment and the population. The safety calculations concerning so-called extended design conditions (the leakage of radionuclides from the WDP) must be retroactively reflected in the design of the WDP and the handling approach (e.g. the design of the ventilation system in the hot chamber). The basic prerequisites concerning the safety assessment comprise a detailed knowledge of the following: the source term, the WDP handling approach and the structures of the WDPs/WPs for SNF and RAW and other DGR components and structures. It will be necessary to evaluate operational safety when changing or modifying the DGR technical design solution in terms of the impacts on the safety documentation for the given site.

5.10.1 Work performed

The update to the Reference Project (Pospíšková et al. 2011) assessed crisis scenarios involving the release of radionuclides into the environment and included the use of preliminary quantitative calculations.

The following scenarios were considered:

- accidents during the manipulation of the transport WP in the repository complex,
- accidents during the loading of SNF into WDPs,
- accidents during the transfer of the WDP to the disposal location.

As part of the DGR site selection process, operational safety studies were conducted for all 9 potential sites for the DGR (Martinčík et al. 2018a-i).

The safety studies included the consideration of release scenarios, the description of radionuclide dispersion models and the creation of models for each site (normal operation and emergency situations) that included estimates of the potential impacts on the health of the population.

All work related to operational safety-related research must be considered as providing support both for the proposed technical design solution and the demonstration of its feasibility and safety.

Lits of SÚRAO archived documentation on safety assessment issues are provided in Holub et al. (1999), Pospíšková et al. (2011) and Martinčík et al. (2018a-i).

5.10.2 Planned and future work

Concerning operational safety, the approach to research and development is difficult to assess without knowing the final nature of the technology, processes and components that will be applied in the DGR. Thus, the R&D will closely follow the project work, especially that related to the handling of RAW. It will focus in particular on the updating and supplementing of data for the assessment of operational safety for the selected disposal concept and related technologies.

The following parameters will be updated for the currently considered sites: the characteristics of the surrounding areas, natural features and phenomena, human-influenced phenomena, characteristics that could influence the dispersion of radioactive substances, factors that could influence the management of emergencies, repository operation factors, the assessment of the impact of the repository on health and the environment, the proposal of limits and conditions, the safe termination of the operation of the DGR, the assessment of quality assurance and the evaluation of the degree of uncertainty of the DGR design solution.

From the point of view of future research, issues related to operational safety and the classical and mining safety of the construction process and DGR operation will be addressed once all the parameters of the DGR have been identified.

5.11 Long-term safety assessment

The long-term safety assessment of the DGR summarises all the scientific and technical aspects pertaining to safety following the closure of the facility. The essential prerequisites for the conducting of the assessment include the accurate description of the site and the properties of the components used in the construction of the DGR. The issues covered by the assessment are conceptually divided into performance assessment and safety assessment considerations.

The performance assessment includes the full range of issues related to the various parts of the DGR and the rock environment, i.e. issues that are not related to the assessment of the radiological impacts in the event of the leakage of radioactive substances from the engineered barrier systems. The main objective of the assessment is to prove that the properties of the components included in the design proposal or already constructed parts of the DGR correspond to those project requirements that primarily concern the need to ensure the safety function of the nuclear facility (see Act No. 263/2016 Coll. paragraph 45). It indirectly follows from the above that the requirements set for the properties of the components include their reliability and service life. As a rule, the performance assessment is conducted before the safety assessment since *inter alia* the performance assessment includes models that map the development of the engineered barriers and other relevant processes in the DGR.

The safety assessment focuses on the assessment of the radiological impacts in case of the leakage of radioactive substances from the engineered barrier systems. The aims are, therefore, primarily to quantify the exposure of a representative person and to assess the impact on the environment (fauna, flora) from the release of radionuclides. The assessment considers scenarios that were identified as part of the FEP analysis. The main radiological indicator is the sum of the effective dose from external radiation and the effective dose duration from radionuclide intake. Concerning the expected development of the DGR, total annual irradiation is compared with the dose optimisation limit.

SÚRAO, will define the respective sets of arguments based on both the requirements of Czech legislation and international recommendations provided primarily in IAEA documentation (IAEA 2009, IAEA 2011a, IAEA 2011b and IAEA 2012) and Posiva and SKB reports (SKB 2011, Posiva 2012), whose safety concepts are very similar to that of SÚRAO.

5.11.1 Work performed

The first comprehensive project aimed at assessing the long-term safety of the DGR and related research activities comprised the SÚRAO *Research support for the safety assessment of the deep geological repository* project (SÚRAO SO2014-061), the main objective of which was to acquire the necessary knowledge, skills and tools for the assessment of long-term safety.

The project was divided into the following areas:

- the behaviour of SNF and other forms of RAW that are unacceptable for disposal in near-surface repositories, in the DGR environment;
- the behaviour of the WDPs for SNF and other RAW in the DGR environment;
- the behaviour of sealing, filling and other structural materials in the DGR environment;
- the design of the disposal wells and their impacts on the properties of the surrounding rock environment;
- the behaviour of the rock environment;
- the transport of radionuclides from the DGR;
- other site characteristics that will potentially affect the safety of the DGR.

The most significant results from the more than 200 research reports that were drawn up as part of the project were summarised in a report by Havlová et al. (2020). The results were also summarised in the form of initial safety report studies for each of the nine potential DGR sites (Vokál et al. 2018a-i). However, the most important output of the project concerned the creation of expert teams that obtained important knowledge and the tools necessary for assessing the long-term safety of the deep geological repository. Moreover, the results of the project provided a basic source of information for the comparison of the candidate DGR sites in terms of long-term safety.

As part of the afore-mentioned project, the migration parameters of samples taken from the surfaces of the potential sites were determined (Havlová et al. 2018k), which allowed for the proposal of the migration parameters for calculation purposes. Furthermore, transport models were created that identified the critical transport pathways for radionuclides into the environment (Říha et al. 2018) for all the potential sites. A follow-up project was subsequently initiated that described the transport of radionuclides in the isolation parts of the DGR, i.e. from the disposal wells up to a distance of approximately 50 m, where the possibility of the occurrence of a category 3 fault was assumed (Gvoždík et al. 2020). This project, which linked the interpretation of one of the fracture networks at the Bukov URF with the transport models, provided important knowledge on the migration of radionuclides in a crystalline environment, which will be used in the compilation of future safety analyses.

The transport parameters and mechanisms of radionuclide transport through the compacted bentonite that will surround the WDPs were summarised in a report by Hofmanová et al. (2019). It was determined that the transport of radionuclides in bentonite includes factors that are difficult to estimate. One of the reasons concerns the variability of the values, which is considerable depending on the experimental conditions. One of the most important findings was that the value of the so-called apparent coefficient (D_a) is not significantly dependent on external conditions. Conversely, the value of the effective diffusion coefficient (De), which is used in safety analyses, is dependent on external conditions. This issue will have to be addressed in future projects.

The transport parameters and transport mechanisms of radionuclides through cement materials, which will comprise a significant component of the DGR, were described in a report by Večerník et al. (2019). One of the most important results concerned the outputs of the sorption experiments presented in the report, which indicated that cement-based materials have significant potential in terms of capturing certain critical, mobile radionuclides (^{129}I, ^{36}Cl) that do not bind to the other barrier materials, such as the rocks of the Bohemian Massif and bentonites, which practically have no sorption function. The project also explored the potential for using mixtures of bentonite and cement, particularly in terms of mitigating the corrosion of the WDP. It was found that carbon steel placed in such mixtures corroded significantly more slowly than when in contact with bentonite; however, localised corrosion could not be excluded (Dobrev et al. 2019). Conversely, no local corrosion was observed when carbon steel was placed in contact with cement alone without the presence of bentonite.

All the knowledge required to calculate the amount of exposure of a representative person was summarised in the preliminary safety analysis conducted for the Kraví hora site (Trpkošová et al. 2018). The report, which was peer-reviewed by a foreign partner organisation (Posiva Solutions), provided a summary of the data acquired in the form of input files for calculation purposes, and included the creation of mathematical and computational models and the calculation of the effective dose and the effective dose duration for selected DGR development scenarios.

As part of the ongoing *Research support for the safety assessment of the DGR technical design solution* project, a database of FEPs has been created. The structure of the FEPs database is based on the established NEA FEPs database. The database is divided into 5 areas: Analysis of FEPs for WDPs with SNF (Pospíšková et al. 2022a), Analysis of FEPs for SNF disposal (Pospíšková et al. 2022b), Analysis of FEPs for the rock environment (Nahodilová et al. 2022), Analysis of FEPs for the biosphere (Husťáková et al. 2022) and Analysis of FEPs for the HLW/ILW repository (Pospíšková et al. 2023a).

Based on the analysis of FEPs in the previous R&D period, scenarios concerning the potential development of the DGR were determined for the section of the repository in which the WDPs with SNF will be disposed of (Pospíšková et al. 2023b) and for:

- the normal development of the DGR corresponding to normal project conditions, and
- the alternative development of the DGR corresponding to extended project conditions.

The normal DGR development scenario was considered for both the most probable development of natural processes and events and for the engineered barriers in terms of their fulfilling all the defined technical specifications (the so-called reference scenario), as well as for a repository development variant that includes both the influence of natural events and potential problem issues with concern to the initially-defined properties of the engineered barriers and, less likely, the processes that are likely to occur in the DGR.

The alternative DGR development scenario is based on events that may occur at the candidate sites, the probability of the occurrence of which is low or very low and which, therefore, are not considered in the basic project conditions. It is possible that the results of the alternative scenarios may not satisfy IAEA SSR 5 recommendations.

5.11.2 Ongoing and planned work

The main objectives for the upcoming period in the field of the long-term safety assessment are:

1) to prepare a safety assessment for the Czech disposal concept (according to TZ 711/2023) for the conditions of the Czech Republic based on archive information on the selected reference site[2] and information provided by research at the Bukov URF and foreign research facilities,
2) to assess descriptive models of the candidate sites with regard to the requirements set out in Decree 378/2016 Coll. (describability and predictability) and subsequently to preliminarily assess the suitability of the candidate sites for the construction of the DGR.

In order to fulfil the objectives defined above, selected research has already been contracted out as part of the *Research support for the safety assessment of the DGR technical design solution* project. This research does not require data from geological survey work at the candidate sites:

- performance and reliability assessment of the barriers of the DGR
- research into the behaviour of radionuclides in the proposed barriers
- creation of conceptual, mathematical and computational models for the DGR safety analysis and
- verification and validation of mathematical and computational models for the DGR safety analysis.

All the above-mentioned research will continue in line with the availability of information on the candidate sites for the selected disposal system. The outcome will comprise a safety study that includes the results of geological exploration work. A list of research activities expected up to 2028 with an indicative schedule is provided in Tab. 18.

[2] Reference site – a hypothetical site located in a suitable block of crystalline rock in the Czech Republic that is used for the general assessment of the Czech disposal concept. It is assumed that the parameters considered for the reference site are average for the Bohemian Massif. Concerning models that require site-specific data, for example the terrain topology (mostly descriptive, e.g. geological, hydrogeological, etc. models), data on the Hrádek site is used.

Tab. 18 Estimated schedule of the key activities planned up to 2028 concerning the long-term safety assessment; indicative schedule showing continuity (outputs to) with key SÚRAO activities according to Tab. 1 in the right-hand column

Activity	FROM	TO	Outputs to
Methodology for the preliminary assessment of the long-term safety of the candidate sites	2023	2024	15
Methodology for the safety certification for the safety assessment of the DGR	2024	2024	15
Performance and reliability assessment of the proposed barriers of the DGR	2021	2026	5
Creation of conceptual, mathematical and computational models for the DGR safety analysis	2021	2026	6
Verification and validation of mathematical and computational models for the DGR safety analysis.	2021	2026	6
Evaluation of the long-term safety of the Czech SNF disposal concept at the reference site	2023	2026	8
Preliminary assessment of the long-term safety of the candidate sites	2027	2029	15

5.11.2.1 Preparation of safety assessment methodology, identification of safety functions and the compilation of scenarios for the long-term development of the repository and the components thereof

The long-term safety of the DGR is based on the passive fulfilment of the safety functions of the natural and engineered barriers, which will ensure the safety of the repository up to the time at which the dose optimisation limit conditions for a representative person are met. The DGR will be a very complex system that will include a large number of components with different properties that will be affected in various ways by the events and processes that occur in the repository over thousands of years.

The output of this stage of the research in terms of the *Research support for the safety assessment of the DGR technical design solution* project will comprise the preparation of a long-term safety assessment methodology that will serve to summarise and classify the various components and define their safety functions.

5.11.2.2 Performance and reliability assessment of the barriers of the DGR

With concern to the DGR, it is difficult to demonstrate the performance and reliability of the repository barriers due to the very long project lifespan and the wide range of influences to which the barriers will be subjected, as set out in section 9 of Decree no. No. 329/2017 Coll. The performance assessment of the disposal barriers requires a thorough understanding of the processes that may take place in the DGR between the various components over thousands of years. Due to the length of time of the required performance of the disposal barriers, it is necessary to rely on predictive models that take into account all the important events and processes that will affect their properties in terms of both time and space.

The main objective of sub-section 2 of the *Research support for the safety assessment of the DGR technical design solution* project - *assessment of the barriers* will be to verify whether the currently proposed barriers will suitably and reliably meet the safety function requirements. Methodologically, it will involve the comparison of the results from the combined thermo-hydro-mechanical-chemical (THMC) modelling of the behaviour of the barriers in the repository with the results of laboratory and in-situ experiments conducted under underground laboratory conditions.

The accurate inclusion of THMC processes in the models will require the continuation of the development of numerical combined process modelling methodologies.

SÚRAO anticipates the continuation of the modelling of the performance and reliability of a double-walled steel WDP surrounded by compacted bentonite emplaced in vertical wells in a crystalline rock environment 500 m below the surface, including:

- the analysis of the influences of corrosion products arising from the contact of carbon steel with compacted bentonite. Concerning the assessment of the long-term impacts of steel corrosion on the bentonite barrier and vice versa, we consider systems that replicate as much as possible the real conditions with respect to both the related experiments and the geochemical modelling (following on from research by Gondoli et al. 2018),
- the evaluation of the generation and transport of gases in the DGR – it must be proven that the gases generated are unable to negatively affect the safety functions of the engineered barriers or that of the rock environment,
- the determination of the influence of groundwater on the properties of the engineered barriers and
- the evaluation of the influence of stress changes in the near field of interactions as a result of the processes that take place in the DGR (following on from research by Hasal et al. 2019, Dobrev et al. 2018).

Experiments that will provide data or information that is not available from other sources may also be included in the research area. The results of the related sub-projects will be provided in research reports that, based on all the available information, will assess the suitability of the proposed barriers for use in the DGR and, if necessary, suggest proposals for their replacement or modification. In addition, further studies will be proposed that focus on the verification of alternative barriers.

The results of experiments conducted at the Bukov URF (see chapter 5.12.2) will also be used for THMC modelling purposes, be they newly-designed experiments aimed solely at the validation of the THMC models or experiments that are already ongoing or planned for other purposes. It will also be possible to use the results of experiments conducted abroad and from the analysis of anthropogenic and natural analogues.

5.11.2.3 Research into the behaviour of radionuclides in the proposed barriers

Damage to the WDPs may lead to the release of the radionuclide inventory into the near and, subsequently, the far fields of interactions. The released substances may include radioactive isotopes, the mobility of which is determined by the chemical, geochemical and retardation properties of the rock environment and the other barriers.

The evaluation of the transport of radionuclides requires a detailed knowledge of the parameters required for the creation of calculation programs (the solubility, sorption and diffusion coefficients) with respect to all the safety barrier materials through which radionuclides are able to pass, under all potential conditions, i.e. taking into account all the FEPs that may occur in the DGR.

Sub-section 3 of the *Research support for the safety assessment of the DGR technical design solution* project - *Research on radionuclides* will focus mainly on critical mobile radionuclides, e.g. ^{14}C, ^{129}I, ^{36}Cl or ^{79}Se and radionuclides that are able to form colloids, or other radionuclides that may exert a significant impact on the safety assessment of the DGR. The objective will be to form a detailed understanding of the processes that affect the transport of critical radionuclides in the DGR and to create, verify and validate models that reflect changes in the transport parameters of critical radionuclides for various DGR development scenarios in terms of both time and space. The research will also include the determination of the transport parameters for various components of the near and far fields of interactions.

The research will take into consideration experimental findings from previous sub-projects of the *Research support for the DGR safety assessment* project (Havlová et al. 2018j; Hofmanová et al. 2019), the *LTD 3* project conducted at the Grimsel underground laboratory aimed at determining the transport parameters in a crystalline rock matrix (Havlová et al. 2018k) and the *SKB Task Force Groundwater* project (Hokr et al. 2020) aimed at verifying the transport of radionuclides in the near field of interactions of crystalline rocks.

A comprehensive set of parameters (solubility, sorption and diffusion coefficients) must be known in order to evaluate the transport of radionuclides through the bentonite barrier. These parameters will be determined experimentally for selected radionuclides as part of the *Development of bentonite barrier parameters* subcontract.

The project will also include the experimental determination of the transport parameters for selected radionuclides in the rock environment following borehole drilling work at the candidate sites.

It is assumed that the results of the *EURAD-FUTURE* project, aimed at improving the understanding of the basic mechanisms of radionuclide migration, and the *CIM* project currently underway at the Grimsel underground laboratory, concerning the study of the migration of radionuclides in a cement environment, will be used in the research.

5.11.2.4 Creation of conceptual, mathematical and computational programs for the assessment of radionuclide transport

Up until the time of the submission to the SÚJB of the application documentation for a licence for the siting, construction, operation and closure of the DGR, it will be necessary to create models for the safety assessment of the repository. The computational models will cover the following:

- The source term (the rate of release of radionuclides from unprocessed SNF),
- The transport of radionuclides in the near field of interactions for the engineered barriers of the Czech disposal concept,
- The transport of radionuclides in the far field of interactions for the reference site,
- The transport of radionuclides in the biosphere for the reference site.

The following models will be created as part of sub-section 4 of the *Research support for the safety assessment of the DGR technical design solution* project - *development, verification and validation of models* and the *Safety analysis* project:

Models for calculating the source term

The preparation of models and input files for the calculation of the source term for the SNF repository. The models will cover mainly the release rates of radionuclides from different parts of the SNF. The influence of various factors on the rate of release of radionuclides and the time and extent of damage to WDPs will also be taken into account.

Models for calculating the transport of radionuclides in the near field of interactions

The near field of interactions comprises the engineered components of, and the rock environment surrounding, the disposal wells. The models will consider the transport of radionuclides from the disposed of waste itself, as well as via corrosion products, the filling materials of the wells and corridors, and the EDZ into water-bearing fracture systems in the rock environment. It is essential to form an understanding of the roles of the various barriers in terms of the rate of transport of radionuclides. The research will follow on from research conducted as part of the *Research support for the DGR safety assessment* project (Trpkošová et al. 2018).

Models for calculating the transport of radionuclides in the far field of interactions

The far field of interactions comprises the rock environment from the near field of interactions to the biosphere.

This research will follow on from the hydrogeological modelling and the determination of the transport properties of the sites, which will be considered in the site descriptive models (Valter et al., 2023).

The creation of the transport in the far field of interactions models for the reference site will use the outputs from the *Research support for the DGR safety assessment* project as summarised in reports by Říha et al. 2018; Gvoždík et al. (2020) , and the results of the *Research support for the safety assessment of the DGR technical design solution* project and other, currently ongoing, projects. The result will comprise the activity concentrations of selected radionuclides at the geosphere/biosphere interface.

Models for calculating the transport of radionuclides in the biosphere

The objective of the research work will be to update the biosphere model for the reference site and various scenarios based on the potential development of the biosphere at the candidate sites.

5.11.2.5 Verification and validation of mathematical models for the DGR safety analysis

The safety assessment of the DGR will require the use of verified and validated models in accordance with the requirements of section 9, paragraph 2 of Decree no. No. 377/2016 Coll. The validation of the models, i.e. the process of determining whether the model provides an adequate representation of the real system, will be conducted on the one hand by comparing various approaches to the creation of models and on the other by comparing the results attained in the Czech Republic and those by foreign DGR programmes. SÚRAO will support the validation of safety assessment models via comparison with models created by foreign partner organisations, e.g. via benchmarking with the results of international projects.

No verified and validated models are currently available from suppliers for the assessment of the long-term safety of the DGR that fulfil the requirements of the SÚJB. It is not possible to simply adopt ready-made computing solutions from abroad without their validation and verification.

The results of experiments conducted at the Bukov URF can also be used to validate computational codes (see chapter 5.13.2). SÚRAO's participation in projects conducted in international underground laboratories is also beneficial in this respect.

The validation of models for the initial safety report and subsequent safety reports related to the approval of the DGR by the SÚJB must comply with the requirements of BN-JB-2.4, with concern to which it will be necessary to implement quality assurance (QA) and quality control (QC) programmes.

5.11.2.6 Assessment of the long-term safety of the Czech disposal concept for unprocessed spent nuclear fuel at the reference site

The research in this area will include:

1) the consideration of the scenarios defined for the safety calculations based on the FEP analysis, including the justification of the selected scenarios, simplifications thereof and the related assumptions,
2) the systematic summarisation of all the information and data for the proposed Czech disposal concept that ensures transparency and allows for the traceability of the data. The range of possible values and their distributions will be estimated followed by the determination of the most likely or conservative values,
3) the assessment of the long-term safety of the proposed DGR technical design solution for the Czech SNF disposal concept
4) the conducting of sensitivity analyses and the assessment of uncertainties and the incorporation of the results into the safety analysis.

5.11.2.7 Preliminary assessment of the compatibility of the candidate sites with the Czech SNF disposal concept

The research will include the conducting of preliminary site safety assessments based on the site descriptive models (Valter et al., 2023) and the use of the results of the long-term safety assessment of the Czech disposal concept for unprocessed spent nuclear fuel at the reference site (Chapter 5.11.2.6). The results will provide an indication of whether the given site is compatible with the proposed DGR technical design solution from the point of view of safety. The complexity of the methodology and the scope of the research will be optimised in relation to the time frame and the capacities of the processing teams.

5.11.3 Future work

Areas that require subsequent research will be identified as part of the assessment of the long-term safety of the Czech disposal concept for SNF at the reference site (SC1). It is expected that the external expert assessment of SC1, the results of which are expected by December 2027, will contribute significantly to the identification of these research areas.

The areas thus identified will be assigned priorities, taking into account their influence on the results of the safety analysis and the requirements arising from the documentation for the siting of the DGR. Follow-up projects will be launched based on the identified priorities.

The methodological approach to the safety assessment, once proven for SC1, will be further developed and improved with the intention of applying the approach to the safety case or the safety analyses required for the siting of the DGR.

It is expected that long-term safety will be proved with respect to the final or backup site and as part of the technical design solution that will be proposed in the *Research support for the project design solution of the DGR for the safety assessment of the disposal concept* project with regard to both the SNF/HLW and ILW sections. This assessment will form part of the documentation submitted for the siting of the DGR nuclear facility according to Act No. 263/2016 Coll., Appendix No. 1 (Initial safety report, chapter Safety assessments). The inventory considered in the scenarios will reflect the requirements of the 2019 Concept.

5.12 Research at the Bukov URF

The Bukov Underground Research Facility (Bukov URF) is intended for the conducting of research, development and demonstration activities connected with the Czech DGR project. The Bukov URF is a generic underground laboratory (according to OECD/NEA 2013), i.e. it is not located at the site intended for the construction of the DGR. The Bukov URF project is based on experience from abroad, especially from countries with advanced DGR development programmes. The purpose of the Bukov URF is to provide space for the conducting of the in-situ experiments required in the current phase of the Czech DGR development concept.

The underground laboratory is located on level 12 of the former Rožná I uranium mine complex (see Fig. 15). The Bukov URF I complex, which was commissioned in 2017, is located in the B-1 shaft area directly beneath the village of Bukov and consists of 475 m of corridors for the conducting of experiments (see Fig. 16). In addition to the first operational part of the laboratory, a new system of laboratory corridors (Bukov II) is currently being excavated. Bukov II is located near to the B-2 shaft, and its position was determined on the basis of the presence of suitable geological conditions, as established via borehole drilling exploration, and suitable technological conditions for the conducting of experiments. The distance between the two sections ensures that ongoing experiments are not impacted by the excavation work. The depths of both parts of the Bukov URF were chosen so as to correspond with the planned depth of the Czech DGR. The corridors of Bukov URF I are located approximately 525 m and those of Bukov URF II 510 m below the surface. The laboratory is located in the crystalline rocks of the Bohemian Massif (Strážecké Moldanubian) and the basic types of rocks present include migmatites, amphibolites and pararules. The facility is operated on behalf of SÚRAO by the former mine operator DIAMO s.p., GEAM division. It is planned that the facility will be in operation until at least 2035.

Up to 2020, mine workings could be accessed to a depth of around 1,200 m (level 24). Currently, however, the underground spaces are limited to those mine workings that are essential for the operation of the laboratory. Normal access is only possible on level 12. Shafts R-1 and B-1 are used for the transport of persons to the underground complexes. Shaft R-6 serves for the ventilation of the mine and shaft B-2 is used for the transport of large loads to the underground complex. The spaces below level 12 have been flooded gradually since March 2021; the level of the groundwater is monitored in shafts R-7S and R-3. Once the groundwater level rises to approx. 60 m below level 12, a new pumping system located in shaft R-7S will be switched on and the water level will be maintained at this level.

The excavation of the Bukov URF II corridor system began in January 2021. The system includes several laboratory corridors each of up to 90 m long, which were excavated perpendicularly from the existing PŠ1-123 transport corridor (see Fig. 17), as well as connecting ventilation corridors and 13 ten-metre long test chambers. The profile of the laboratory corridors and test chambers is 14.8 m^2. The connecting ventilation corridors have a profile of 7.7 m^2. The complex was excavated via the contour blasting method according to a specially adapted drilling scheme with a maximum excavation of 2 m. It is expected that the excavation work will be completed in the second quarter of 2024. The commissioning of this part of the URF is planned for 2025.

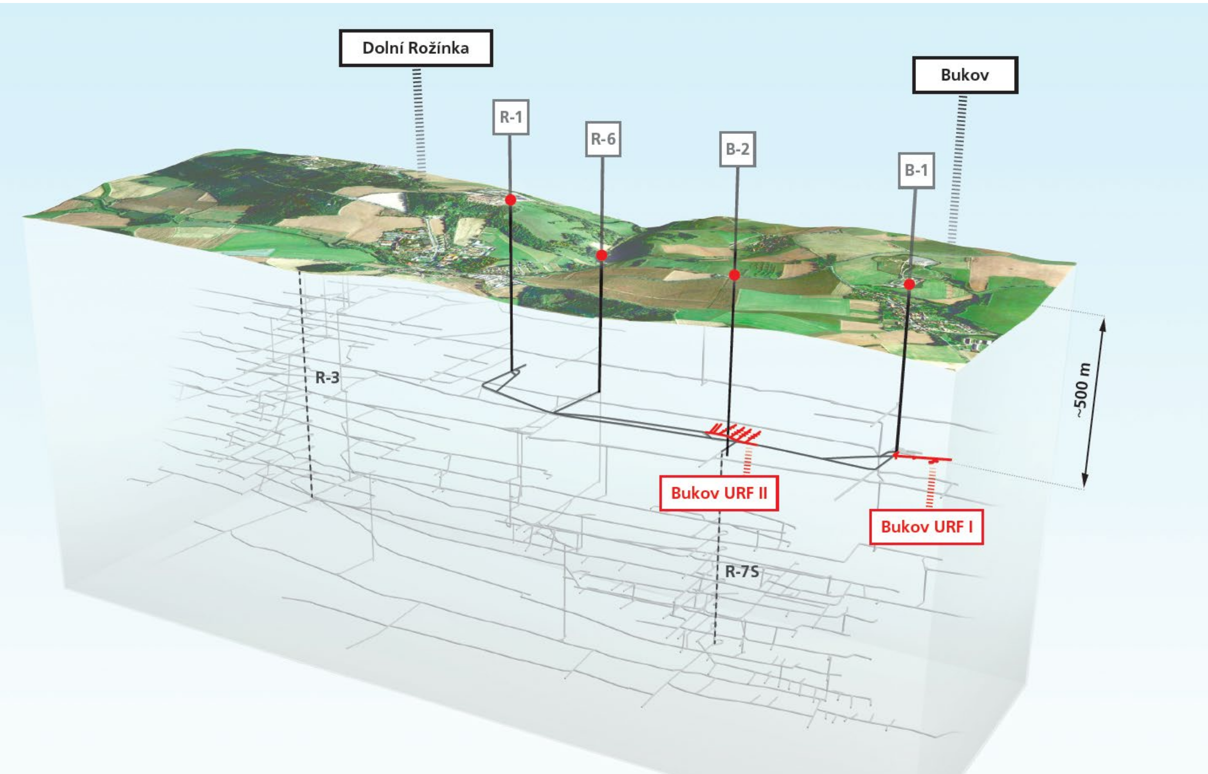

Fig. 15 Scheme of the Rožná I mine complex showing the operational areas

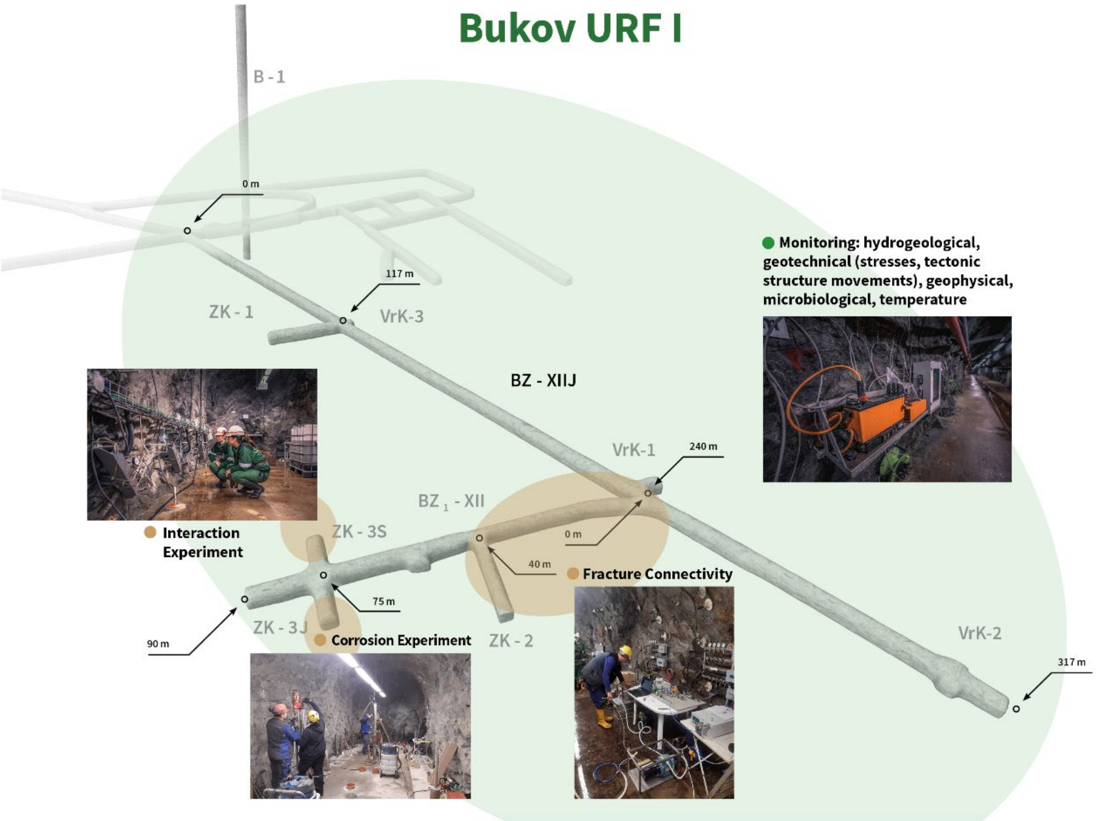

Fig. 16 Scheme of the Bukov URF I laboratory corridors showing the locations of the key experiments

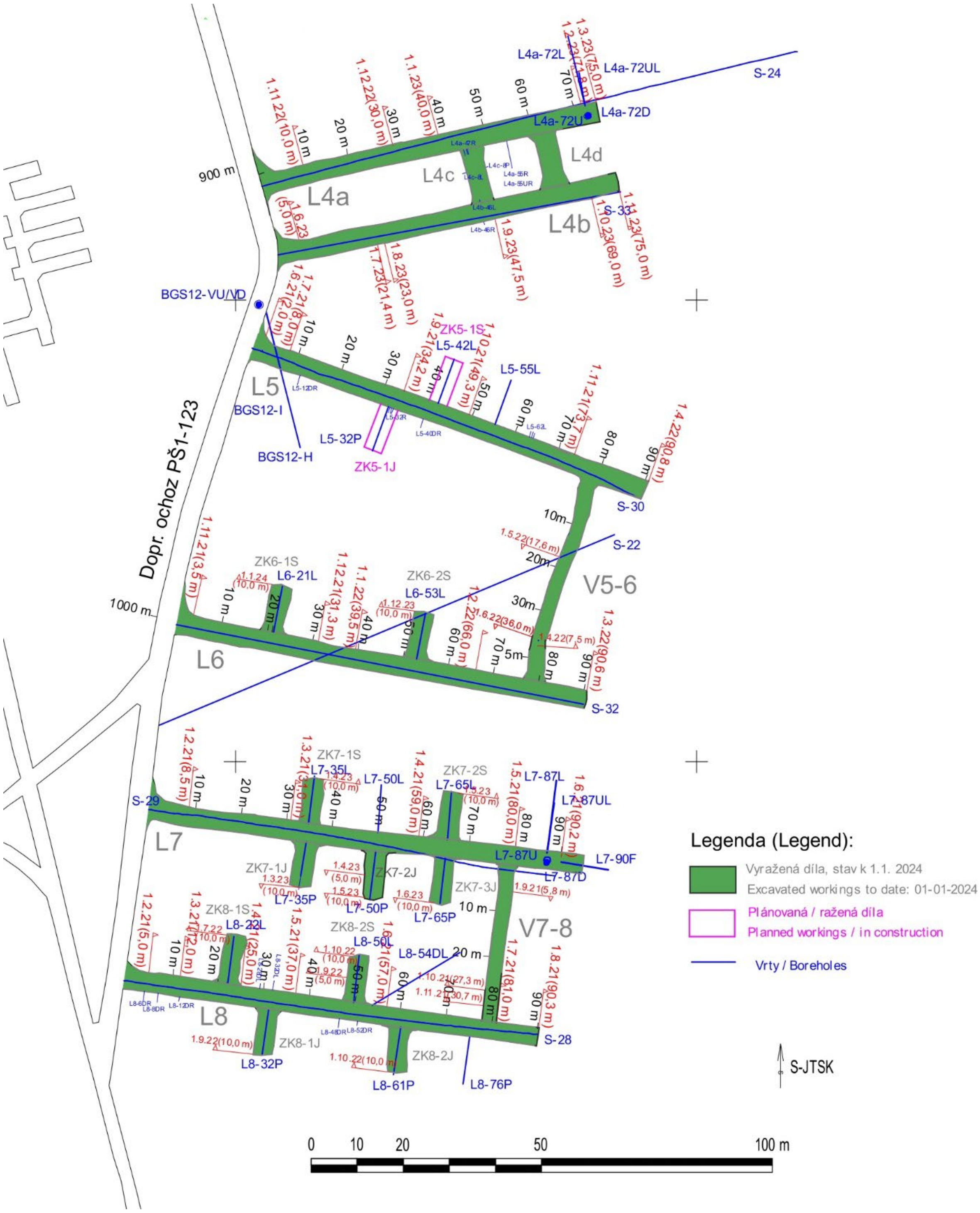

Fig. 17 Map of Bukov URF II (as at 1 January 2024)

5.12.1 Work performed

Since its commissioning, the research, development and demonstration activities at the Bukov URF have been divided into 7 key areas referred to as REPs (research and experimental plan). The basic objectives of the 7 areas are listed in Tab. 19.

Tab. 19 Basic areas of the Research and Experimental Plan for the Bukov URF

REP	Abbreviated name	Objectives
1	Characterisation	Development of rock environment description methodologies. Collection of descriptive geological data, its database storage and interpretation in the form of 3D models.
2	Monitoring	Testing and development of methods for the long-term monitoring of processes that occur in the rock mass (hydrogeology, movement of brittle structures, microbiological settlement, temperature of the rock mass, seismicity). Development of non-destructive geophysical methods.
3	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.
4	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.
5	EDZ	Development and testing of methods for the characterisation of damaged (EDZ) and disturbed (EdZ) areas of rock in the vicinity of the underground spaces.
6	Technological procedures	Development of new procedures for the construction of underground workings (drilling and excavation work, grouting, excavation in fault zones).
7	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.

A detailed description of the experimental work conducted at the Bukov URF since the commencement of operation is provided in SÚRAO report No. 683/2023 (Smutek et al. 2023). A basic overview of completed projects with an indication of their duration and links to the respective final reports is provided in Tab. 20.

Tab. 20 List of completed projects at the Bukov URF

Project name	Contract name	Duration	Main affected REP area
Characterisation I	Comprehensive geological characterisation of the Bukov URF (Bukovská et al. 2017, Souček et al. 2018)	2013 - 2017	1
EDZ I	Creation and monitoring of EDZ during the construction of the Bukov URF (Staš et al. 2019)	2015 - 2018	5

Project name	Contract name	Duration	Main affected REP area
Microbiology I	Microbial screening of the Bukov URF and Rožná mine (Steinová et al. 2019)	2017 - 2019	2
Deep horizons	Acquisition of data from the deep horizons of the Rožná mine (Bukovská et al. 2020)	2017 - 2020	1
Hydromonitoring I	Hydrogeological and hydrochemical monitoring of underground and mine water in the Bukov URF (Vylamová et al. 2023)	2018 - 2023	2
Non-destructive geophysics	Long-term monitoring of the rock mass in the Bukov URF using non-destructive geophysical methods (Bárta et al. 2022)	2018 - 2022	2
Brittle structures	Monitoring of the activity of brittle structures in the Bukov URF and the Rožná mine (Stemberk et al. 2022)	2018 - 2022	2
Microbiology II	Monitoring of anaerobic microbial settlement in the Bukov URF and research into the links between the rock environment and microbes (Steinová et al. 2021, Černá et al. 2021)	2020 - 2021	2
Seismic URF II	Determination of the spatial homogeneity of the environment before carrying out blasting work using seismic tomography (Chabr et al. 2021)	2020 - 2021	1
POSIVA FLOW LOG	Posiva Flow Log measurements in four boreholes at the Bukov underground research facility in the Czech Republic (Komulainen et al. 2023)	2022	3
GEOSTAB	Development of geotechnical and geophysical methods for obtaining 2D and 3D images of geological structures (external project)	2017 - 2021	2
GEOBARR	Long-term research of geochemical barriers for nuclear waste disposal (external project, ÚGV MUNI 2023)	2018 - 2022	1

5.12.2 Ongoing and planned work

An overview of ongoing projects at the Bukov URF is provided in Tab. 21. More detailed descriptions of the projects accompanied by selected interim results are provided in SÚRAO report No. 683/2023 (Smutek et al. 2023). Tab. 22 provides an overview of planned projects that are expected to commence in 2025 at the latest and which are currently in the preparation stage.

The previous version of the SÚRAO R&D plan (2020) defined a total of 7 objectives on which the Bukov URF research programme should focus especially in the period 2023 - 2024. An assessment of the current status of the objectives is provided below.

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 completed Characterisation I project (Bukovská et al. 2017), for example, provided enough data to allow for the defining of the vertical zonality of groundwater from the surface to a depth of 1,200 m. The Deep Horizons project (Bukovská et al. 2020) subsequently provided data for the interpretation of changes in the geological parameters of the rock with depth and information on the impacts of the presence of a large-scale fault structure on the extent of the tectonic failure of the surrounding rock. The development of rock classification systems for use in the process of the siting, construction and operation of the DGR is being addressed in the ongoing Characterisation II project (Bukovská et al. 2022).
It was planned that additional data concerning this objective would be provided by a project involving the drilling of a deep borehole from the surface to the depth of the Bukov URF, as mentioned in previous R&D plans (Vokál et al. 2020, Smutek et al. 2020); however, based on the development of the DGR programme in recent years, the shortening of the DGR preparation process (Taxonomy) and the expected launching of deep borehole research at the candidate sites, this experiment was seen as surplus to requirements and was removed from the Bukov URF R&D plan.

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 (Steinová et al. 2019). Local microbial diversity was defined based on the collection and analysis of water samples and microbial growth on the rock in various parts of the Bukov URF and the Rožná mine. Microbial activity is also being monitored in the Interaction Experiment (Svoboda et al. 2022). The Microbiology II project (Steinová et al. 2021, Černá et al. 2021) focused on the evaluation of the composition of the microbial settlement of groundwater under anaerobic conditions and its interpretation in relation to the microbial composition and the hydrochemical conditions in flooded monitoring boreholes. Based on expert recommendations, it was decided that this research area would no longer be addressed separately, but would be linked to other experiments, an example of which is the ongoing Corrosion Experiment, which includes related monitoring and analysis activities (Dobrev et al. 2022).

3) **Verification of heat dissemination in the DGR using sources that simulate SNF**
The key to the DGR project design solution concerns the verification of the dissemination of heat in the DGR via experiments that simulate the residual heat generated by the SNF; this issue will impact the layout of the underground passages and disposal wells in the DGR.
This issue is being partly addressed in the ongoing Interaction Experiment (Svoboda et al. 2022), which is providing data on the distribution and development of temperature inside and around heated physical models containing bentonite. The research includes

the creation of mathematical models of the propagation of heat in the rock block in the vicinity of the physical models. A project concerning the dismantling of this experiment is scheduled to begin in 2024.
The issue of the temperature parameters of the rock mass is being addressed in the ongoing Thermal Monitoring project (Dědeček et al. 2022), the aims of which include the determination of the thermal gradient and defining the impact on the temperature of rock masses due to the excavation and operation of mine complexes.
In-situ experiments that include the construction of physical models of disposal sites are planned aimed at the further research of this area, especially the HEAT experiment (see Tab. 22), the preparation of which will include a project for the testing of the construction and the characterisation of large-profile boreholes, the start of which is planned for 2024.

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 and related processes such as sorption will be conducted in order to verify the prediction of the transport of mobile radionuclides in the isolation part of the DGR. This research area is being addressed via the ongoing Fracture Connectivity project (Zuna et al. 2022), which involves the use of tracer tests in a series of test boreholes equipped with multipacker systems. The in-situ research is accompanied by a modelling programme involving the creation and refinement of a structural geological and hydrogeological model of the studied rock block and the simulation of hydraulic testing. The experimental plan envisages a possible follow-up project to be conducted at the existing site in Bukov URF I and in the new Bukov URF II complex. This objective is also related to the planned DFN modelling project, which will use data obtained from the Bukov URF environment.

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 (Dobrev et al. 2022).

6) **Verification of the prediction of THMC processes under real DGR conditions**
Information obtained from ongoing and planned in-situ experiments concerning the creation of physical models of disposal spaces will be used to fulfil this research objective. Ongoing experiments include the Interaction Experiment and planned experiments include the HEAT (see Tab. 22), ERO and EXP (see Tab. 23) experiments.

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 refers to the verification of the influence of the excavation of underground spaces on the extent and parameters of the damaged (EDZ) and influenced (EIZ) areas of the rock mass in the vicinity of underground corridors. This topic is being addressed on a continuous basis, and the most relevant information is

being provided by the characterisation and other research activities being conducted in parallel with the construction of the new laboratory corridors of the Bukov URF II complex (Bukovská et al. 2022). The ongoing Contour Blasting project aims to compare different blasting procedures and their impacts on damage to rock masses. The in-situ Pore Pressure experiment is intended to provide information on changes in pore water pressures in the rock mass in the vicinity of the excavated corridors, which will subsequently be used for the modelling of the development of EDZ.

Tab. 21 List of ongoing projects in the Bukov URF; schedule showing continuity (outputs to) with key SÚRAO activities according to Tab. 1 in the right-hand column

Project name	**Contract name**	**Duration**	**Main affected REP area**	**Outputs to**
Interaction experiment	In-situ interactive physical models in the Bukov URF (Svoboda et al. 2022)	2017 - 2026	4	10
Fracture connectivity	Investigation of the fracture connectivity in the Bukov URF (Zuna et al. 2022)	2019 - 2024	3	6 and 9
Characterisation II	Geological and geotechnical characterisation of the rock environment – Bukov URF II (Bukovská et al. 2022)	2021 - 2025	1	12
Corrosion experiment	Pilot corrosion experiment in the Bukov URF (Dobrev et al. 2022)	2021 - 2034	4	10
Temperature monitoring	Temperature monitoring of the rock mass in the Bukov URF and Rožná I mine (Dědeček et al. 2022)	2021 - 2025 (2030)	2	11 and 14
MAGIC	EURAD – WP MAGIC	2021 - 2024	4	10
Stress	Determination of in-situ stress in the Bukov URF II	2023 - 2025 (2027)	2	12
Contour blasting	Contour blasting work during the excavation of a test chamber in the Bukov URF	2023 - 2024	6	11
Pore pressures	Pore pressure monitoring in the Bukov URF	2024 - 2025 (2027)	5	6
Hydromonitoring II	Hydrogeological monitoring of surface, underground and mine water in the Bukov URF	2023 - 2025	2	12

Tab. 22 List of planned projects in the Bukov URF; indicative schedule showing continuity (outputs to) with key SÚRAO activities according to Tab. 1 in the right-hand column

Project name	**Expected content**	**Duration**	**Main affected REP area**	**Outputs to**
Dismantling of the Interaction Experiment	Dismantling of the physical interaction models of the experiment and the analysis of samples of materials for the evaluation and interpretation of the interactions.	2024 - 2027	4	10
Large-profile boreholes	Testing of the realisation and characterisation of large-profile disposal boreholes for the emplacement of WDP models (experiments related to engineered barriers).	2024 - 2025	6	For other in-situ experiment s
Long-term laboratory	Creation of a set of reference samples of candidate materials for the engineered barriers and other construction materials and their storage under various conditions and combinations for the study of their long-term behaviour and interactions.	2024 - 2034	4	10
DFN modelling	Validation of models of the geometry of fracture networks and flow in fractured environments that will be used to describe flow conditions at the candidate sites.	2024 - 2027	3	6
Fracture connectivity II	Continuation of the study of substance transport processes in the fractured environment of crystalline rocks using tracers and a related mathematical modelling programme.	2024 - 2030	3	6
HEAT	Construction of a physical model of a DGR disposal space with an emphasis on the monitoring of the propagation of heat from the WDP through the bentonite barrier and into the host rock.	2025 - 2031	4	11
Monitoring and modelling of the rock mass	Follow-up and supplementary monitoring programme concerning the various parameters of the rock mass (hydro-monitoring, movements of brittle structures, geostatic stress, etc.), the research	2025 - 2034	2	After 2028

Project name	Expected content	Duration	Main affected REP area	Outputs to
	and development of non-destructive geophysical methods and the related modelling of the area of interest with an emphasis on addressing the interconnectedness of the various parameters.			

5.12.3 Future work

Future research will include the more advanced experiments listed in Tab. 23. The ERO project aims to determine the rate and speed of the erosion of a bentonite barrier due to advective flows in the fracture systems of the host rock with concern to Czech Ca-Mg bentonite, to assess the stability and sealing capabilities of the bentonite and to define the conditions for the formation of colloidal particles in real rock mass conditions.

The EXP project includes an in-situ experiment involving the construction of a vertical model of a disposal space, including part of the adjacent disposal corridor. The aims include the verification of potential installation techniques for the mock-up WDP and the buffer, addressing the dimensions and design of the spacer block in the disposal well, and the verification of the mechanical stress acting on the WDP due to the swelling of the bentonite for various buffer saturation scenarios.

The so-called Demonstration experiment will comprise the final complex experiment at the Bukov URF and will involve the construction of a prototype repository. The demonstration of the vertical WDP disposal system is currently being considered. This project will make use of the results of previous experiments that addressed the development of engineered barriers.

Tab. 23 List of future projects at the Bukov URF

Project name	Expected content	Duration	Main affected REP area
ERO	In-situ experiment on bentonite erosion and the transport of colloids.	2026-2031	4
EXP	In-situ experiment with the priority aim of studying the expansion of the buffer into the backfill.	2027-2034	4
Demonstration experiment	Comprehensive experiment aimed at proving the feasibility and performance of the various considered DGR technical design solutions.	2027-2034	7

6 Research and development activities - operational repositories

SÚRAO currently operates 3 radioactive waste repositories: Dukovany, Richard and Bratrství. Research activities concerning operational repositories are related primarily to SÚRAO's basic obligations to conduct safety assessments on a regular basis, as well as special safety assessments in the event of changes in terms of the use of nuclear energy (Act No. 263/2016 Coll., section 48) of the repositories. It is necessary to enhance the level of nuclear safety to a reasonably feasible extent on the basis of the safety assessment (Act No. 263/2016 Coll., section 49) from the point of view of the current level of science and technology (Act No. 263/2016 Coll., section 5) and to evaluate the factors that are decisive in terms of assessing the acceptability of sites for the siting of nuclear facilities. Thus, it is necessary to continuously monitor the development of science and technology and to apply the findings aimed at continuously enhancing nuclear safety. A further important reason for conducting such research and development concerns the need to ensure sufficient capacity for the disposal of all types of radioactive waste that are, and are expected to be, generated in the Czech Republic. Research and development in this area can be divided into three areas:

1) The updating of the safety assessments of operational repositories up to 2026,
2) The application of new findings aimed at enhancing nuclear safety and radiation protection,
3) Ensuring sufficient disposal capacity for the disposal of all the waste generated in the Czech Republic.

The chapters below provide descriptions of the three operational repositories and the planned research activities that will contribute to the fulfilment of the above-mentioned objectives.

The final chapter addresses the issue of the disposal of NORM/TENORM waste, i.e. waste that contains natural radionuclides. Addressing this issue is one of the objectives set out in the Concept (2019).

6.1 Description of operational repositories

6.1.1 Dukovany

The near-surface Dukovany repository (see Fig. 18) is located in the southeastern part of the Dukovany NPP (EDU) complex. This repository was put into permanent operation in 1995 and serves mainly for the disposal of RAW from the operation of the Dukovany (EDU) and Temelín (ETE) NPPs. The total disposal volume of the repository is approx. 55,000 m^3 (around 180,000 200 l drums) and will be sufficient to receive all the RAW from the operation and decommissioning of EDU and ETE that meets the conditions for acceptability for disposal, even in the case of the extension of their operation to 60 years, and waste from one new nuclear source (NNS).

The layout of the repository (see Fig. 19) consists of two double rows of chambers constructed from ordinary reinforced concrete, class B II – B.22. The floors of the chambers are slightly sloped and have been coated with a layer of paint. 2 sealing layers of APB (asphalt-propylene micro concrete) have been applied below the floors, shown in the image as APC = asphalt-propylene concrete, both of which are 15 cm thick and are separated by a gravel drainage layer. The sides of the chambers also feature a sealing layer of APB with a thickness of 40 cm; 30 cm at the ends of the walls. The APB insulation layer thus forms an impermeable barrier around the disposal chambers and its main task is to protect the chambers from the inflow of water. 4 layers of materials (partially visible in the image below) were installed beneath the foundation joints of the repository concrete panels:

- a layer consisting of macadam and soil (0.9 m),
- a layer of loamy-sandy gravel (2.2 m),
- weathered bedrock and
- unweathered bedrock (gneisses and granulites at a depth of 4.5 m).

The repository consists of two double rows of reinforced concrete chambers. Each row is divided into 7 expansion units each containing 4 chambers. The total number of chambers is 112. The filled chambers are covered with 14 roof panels consisting of 3 types, one of which features a hole for the detection of the presence of water in the covered chambers and its removal if necessary. The cover panels slope slightly to allow for the drainage of rainwater. The chambers were constructed to resist both external groundwater pressure and internal flooding water pressure, the roof panels the weight of a truck and the base panels the pressure resulting from the filling and permanent covering of the chambers. The watertightness of the disposal chambers is ensured by the APB sealing layer. A crane track is located on the upper edges of the longitudinal walls of the double rows, along which a gantry crane with a load capacity of 1t/12.5t and a mobile shelter operates for the handling of the waste containers.

The safety of the repository during the operational period is ensured by a monitoring system in accordance with the Monitoring Programme of the Dukovany repository (SÚRAO directive S.17) as approved by the SÚJB. The operation and method of closure of the repository are required to be subjected to safety analyses. The repository is operated on the basis of an operating licence issued by the SÚJB.

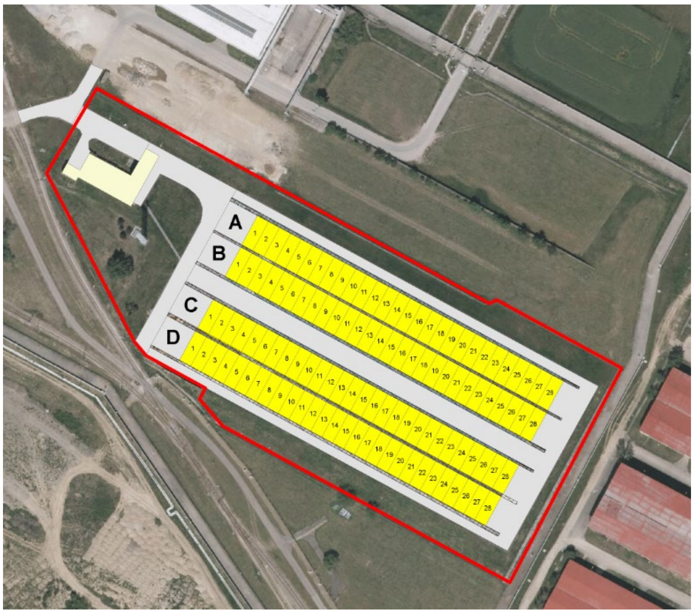

Fig. 18 Layout of the Dukovany repository showing the double rows of disposal chambers

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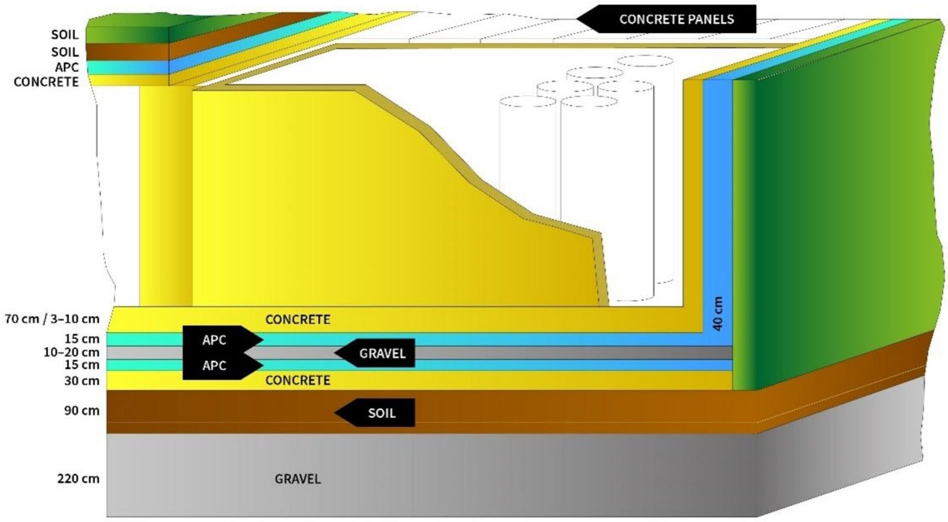

Fig. 19 The structure of the Dukovany repository

6.1.2 Richard

The Richard repository, located in the former Richard mine on the northwestern edge of the town of Litoměřice, was put into permanent operation in 1964 for the disposal of institutional low- and intermediate-level waste, i.e. radioactive waste that is generated in the healthcare, industry, agriculture and research sectors. The reconstruction of the Richard repository in 2019-2021 was aimed at increasing the capacity of the facility (Fig. 20). The reconstruction and stabilisation of the new areas will continue aimed at ensuring disposal and storage capacity for the next several decades.

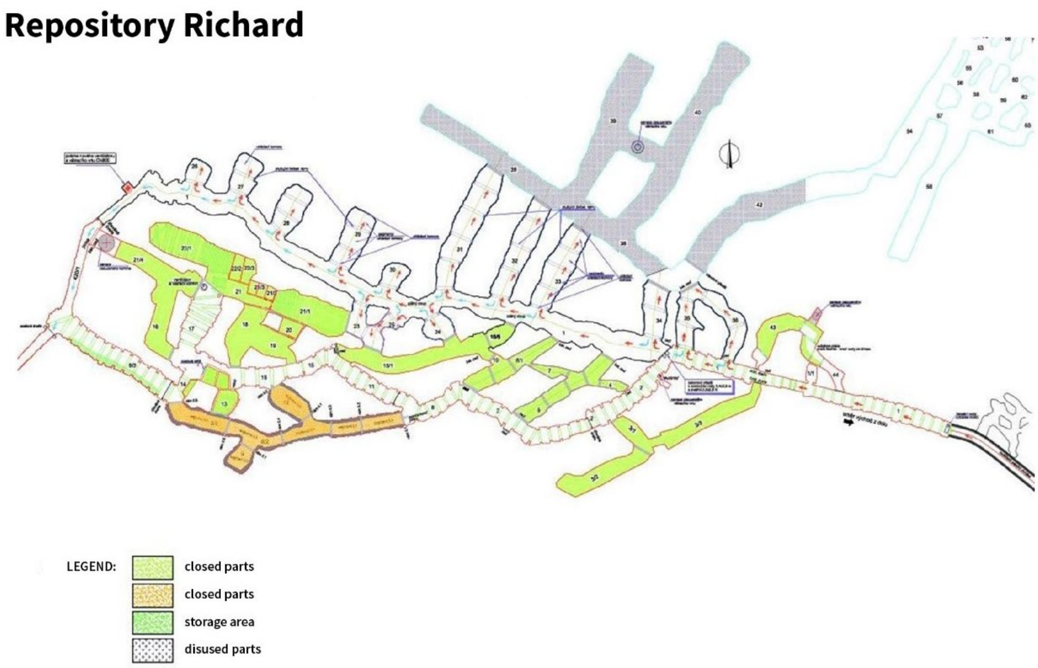

Fig. 20 Layout of the underground complex of the Richard repository following reconstruction

6.1.3 Bratrství

The Bratrstvi underground repository, used for the disposal of waste containing only natural radionuclides, is located in the former Bratrstvi uranium mine located near the town of Jáchymov; it was put into permanent operation in 1974 (Fig. 21). Future research will concentrate on the stabilisation of already disposed of treated waste in the disposal chambers, and a strategic decision will be made on the eventual closure of the repository once the disposal capacity has been exhausted or the expansion of the disposal capacity by adapting part of the access corridor for the disposal of treated RAW. These activities will be of a purely engineering rather than a scientific-research nature.

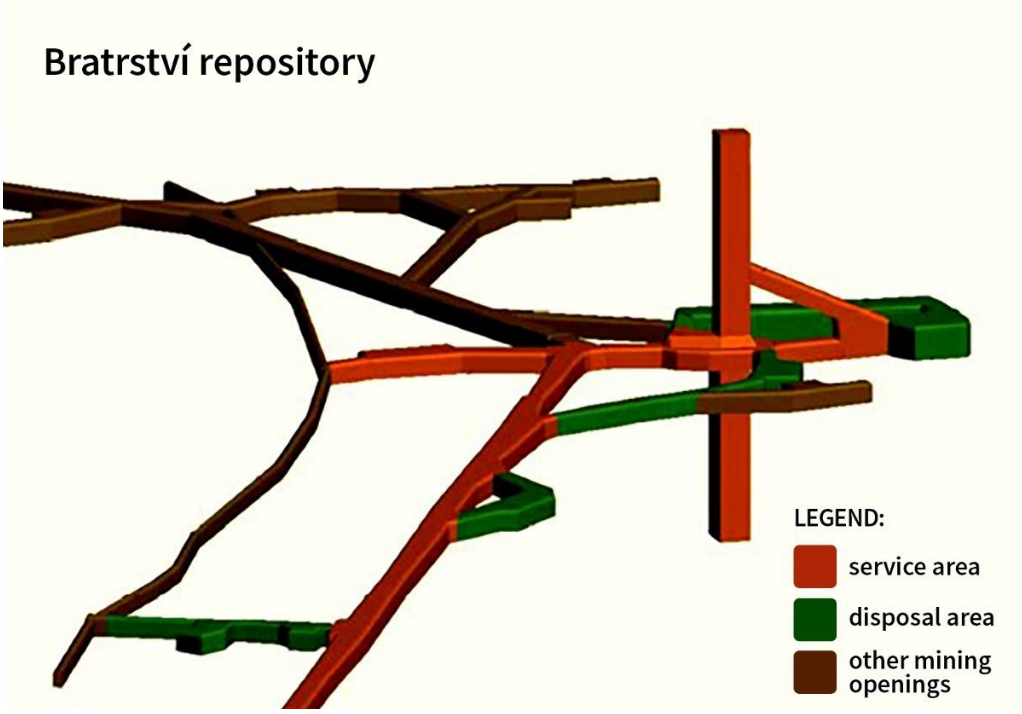

Fig. 21 Layout of the Bratrství repository

6.2 Ongoing and planned work

The Preparation of safety analyses for the periodic safety assessment of operational radioactive waste repositories (Richard, Bratrství and Dukovany) project was launched in 2021 (see Appendix 1, SO2020-085). The project, which should be completed in 2027, serves to fulfil the legal requirement to perform safety assessments in a regular, systematic, comprehensive and verifiable manner on the level of nuclear safety, radiation protection, technical safety, monitoring of the radiation situation, management of radiation emergencies and security. The aim of the project concerns the completion of periodic safety assessments of all three operational repositories up to 2026.

The research topics concerning operational repositories are determined primarily by the need for obtaining the information required for the safety analyses, as well as the monitoring of new trends in the disposal of radioactive waste. Tab. 24 provides a summary of the research planned for the upcoming period to 2028 with an indicative time schedule; the research areas are described in detail below. The research will provide information for the fulfilment of one of

SÚRAO's main objectives, i.e. the periodic safety assessment of operational repositories and the related supplementary research (see chapter 4).

Tab. 24 Estimated schedule of key R&D activities planned up to 2028 in the area of operational disposal facilities; indicative schedule

Activity	FROM	TO
Study of new RAW disposal trends	2026	2028
Updating of the engineered barriers surveillance programme	2025	2026
Research into the ageing of bitumen matrices at the Dukovany repository	2026	2028
Assessment of the condition of the second double row of chambers (A,B) at the Dukovany repository	2025	2027
Proposal for the final covering of the Dukovany repository	2028	2030

Study of new RAW disposal trends

The RAW disposal concept in the Czech Republic is well established, is fully in line with European practice and legislation and has been verified via the safe operation of disposal facilities over several decades. However, Czech nuclear legislation requires the monitoring of new trends and technologies. The aim of this project is the research of new technologies offered by specialist companies in the Czech Republic and worldwide, which must subsequently be compared with the set limits and conditions of the RAW disposal facilities, taking into account the safety functions of the filling materials and potential new types of WPs, and the use-up of the disposal capacity of the repositories.

In the case of the Dukovany repository, in connection with the construction of new nuclear sources, it will be necessary to commence research into the potential expansion of the facility with respect to the disposal of the waste produced by NNS. Moreover, research should consider the filling of row D of the Dukovany repository and the transfer of the gantry crane to row C, as well as the evaluation of the condition of the second double row of chambers (A, B) at the facility.

Updating of the engineered barriers surveillance programme

A system for the extraction of so-called surveillance samples of structural and filling concrete materials from the disposal chambers at the Richard repository has been in place since 2009. However, no systematic assessment of the state of the engineered barriers and construction materials that affect safety has been performed to date. Therefore, it is planned that the results of the analysis of the surveillance samples will be used for this purpose going forward. The main objective is the updating of surveillance programmes at all the repositories.

Research into the ageing of bitumen matrices at the Dukovany repository

Bitumen is used as a hardener/matrix for liquid waste produced via the operation of nuclear power plants. Compared to other types of matrices, bitumen has a number of advantages (a high degree of filling, good fixation of radionuclides/leachability), whereas its flammability comprises a disadvantageous property. Due to this potential safety risk, this form of matrix is not used worldwide and certain countries avoid the use of this technology. The research project will focus on the monitoring of the long-term behaviour of bitumen in near-surface repositories under varying weather conditions. This type of matrix will not be used for RAW from NNS; however, it is likely to constitute the main treatment method for liquid RAW produced in existing NPPs. The parameters to be investigated concern mainly the physical state of the material and its retention capacity (= the leachability of radionuclides).

Assessment of the condition of the second double row of chambers (A,B) at the Dukovany repository

The A,B double row disposal chambers at the Dukovany repository have already been built, however their use is not expected for another approx. 30 years. The project will serve to verify the current state of the concrete structures and to determine a method for their protection/preservation up to the time of use. The research may also focus on the potential for improving the insulation function of the double rows, for example by impregnating the inner walls of the chambers prior to disposal. The examination of the condition of the concrete structures of the double rows of disposal chambers is connected to the legal requirement for the controlled ageing of selected equipment, in this case the structural concrete of the disposal facility. The investigated parameters will comprise primarily the pH, diffusion coefficients and the physical state of the concrete structures.

Proposal for the final covering of the Dukovany repository

The operation of the Dukovany repository is planned for the duration of the operation of existing NPPs as well as during the period of NPP decommissioning fully taking into account the extension of their service lives and the construction of one NNS.

The end of operation and closure of the repository are, therefore, not expected for at least the next 50 years. Nevertheless, it is assumed that research will be conducted on the current proposal for the repository closure method. The proposal considers the final covering of both (and possibly a third) double rows of chambers, i.e. the method for the covering of the disposed of materials and the structure of the repository. The proposal should also take into account the proposed method for subsequent institutional inspection.

Research into the treatment of organic liquid RAW

Liquid organic radioactive waste is created mainly in the institutional sphere in the form of scintillation solutions; moreover, waste such as contaminated oil may also be created during the operation of nuclear power plants. Although the volume of such waste is low, the treatment technology used for aqueous liquid wastes cannot be used for such waste from the chemical-physical point of view. Processing in the form of combustion or distillation requires very special equipment, which is not economically sustainable due to the small quantities involved. Therefore, the question arises as to how to suitably fix such waste prior to treatment using a hardener (cementation). Currently, such waste is fixed via by sorption into an inorganic sorbent (perlite), following which the sorbent is poured into a cement matrix. The concern here is whether this treatment method, i.e. sorption, will continue to prevent the release of the sorbed liquid should there be a change in the environmental conditions (e.g. in terms of the temperature). The project will focus on proposals for alternative approaches to fixing organic liquid wastes prior to solidification in the cement matrix.

6.3 Future work

Future research concerning operational repositories will depend on the results of the already planned research, as well as on the update of the Management of Radioactive Waste and Spent Nuclear Fuel Concept in the Czech Republic, including plans for the construction of new nuclear power plants and small modular reactors (SMR). Most of the future work concerning operational repositories will be of an engineering rather than a scientific-research nature.

7 Disposal of NORM/TENORM waste

This issue is currently being addressed by the State Institute for Radiation Protection based on a study agreement on the issue of the handling of selected waste that contains natural radionuclides that do not originate from radiation activities (contract no. SO2023-06). The second stage of the study has already been completed and it is expected that the study will be concluded in Q3 of 2024.

The main objectives of the study concern the inventorisation, characterisation and prediction of the formation of radioactive substances released from workplaces with materials with enhanced contents of natural radionuclides. The study will critically evaluate existing options for dealing with NORM-type problematic radioactive substances and propose long-term sustainable and economically optimised solutions for their disposal, including a legal analysis and suggestions for potential changes to related legislation.

The results of the project to date provide a description of the impacts of current structural changes with respect to the industrial base of the Czech Republic, including the significant decline or disappearance of entire traditional production sectors that typically generated NORM/TENORM waste due to a loss of competitiveness in the global market and pressure to transition to a low-carbon economy (the production of electricity from coal, primary iron production, chemical industry, etc.). With concern to these industries, the main issue will concern the one-off generation of waste during the dismantling of technological equipment and the rehabilitation of vacated areas. Moreover, the research of foreign sources suggests that the generation of NORM waste from newly developing activities, such as the use of geothermal energy, will become increasingly important.

A proposal to introduce a system for dealing with such materials, including economic optimisation considerations, forms the subject of the final stage of the project, the completion of which is expected on 31 August 2024.

8 Conclusion

The SÚRAO research and development plan is drawn up for five-year periods and is aimed at assisting to fulfil SÚRAO’s main objectives: the selection of a final and backup site for the DGR by 2030, the updating of the technical design of the DGR, the safety assessment of the DGR disposal concept and the periodic safety assessment of the Dukovany, Richard and Bratrství repositories up to 2026.

The document presents research activities according to various expert areas, from the SNF inventory, through geology and engineered barriers to research connected with operational repositories. An indicative schedule is provided for each research area, the observance of which should ensure the fulfilment of SÚRAO’s main objectives.

The addressing of the various planned research and development activities may lead to the emergence of supplementary or unexpected issues that could require the expansion of the respective research field.

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10 Appendix 1 – List of ongoing projects relevant to R&D

Contract no.	Project name	Duration
SO2017-053	In-situ interactive physical models at the Bukov URF	01/2017–12/2024
SO2019-004	HotBent	01/2019–12/2027
SO2019-031	Research of fracture connectivity at the Bukov URF	01/2019–12/2024
SO2020-032	DOPAS-EPSP	03/2021–03/2024
SO2020-085	Preparation of safety analyses for periodic assessment of the safety of operational radioactive waste repositories	03/2021–03/2027
SO2020-086	Pilot corrosion experiment at the Bukov URF	05/2021–07/2035
SO2020-087	Geological and geotechnical characterisation of the rock environment – Bukov URF II	01/2021–12/2025
SO2020-092	Fillings and other engineered components of the DGR	11/2021–03/2026
SO2021-007	Research support for the safety assessment of the DGR technical design solution, part 1 Analysis of FEPs	07/2021–07/2025 (realisation of sub-projects to 07/2027)
SO2021-053	Research support for the safety assessment of the DGR technical design solution, part 2 Assessment of barriers	07/2021–07/2025 (realisation of sub-projects to 07/2027)
SO2021-054	Research support for the safety assessment of the DGR technical design solution, part 3 Research of radionuclides	07/2021–07/2025 (realisation of sub-projects to 07/2027)
SO2021-061	Research support for the safety assessment of the DGR technical design solution, part 4 Development, verification and validation of models and Safety analyses	07/2021–07/2025 (realisation of sub-projects to 07/2027)

Contract no.	Project name	Duration
SO2021-085	Thermal monitoring of the rock mass in the Bukov URF and Rožná I mine	01/2021–12/2030
SO2021-110	Horizontal cooperation between SÚRAO and ČGS in the field of geological research on potential sites for the DGR	12/2021–12/2030
SO2022-008	Updating of the inventory and characteristics of radioactive waste intended for the DGR - part 1 SNF update	03/2022–12/2024
SO2022-009	Updating of the inventory and characteristics of radioactive waste intended for the DGR - part 2 HLW/ILW update	03/2022–12/2024
SO2022-018	Research support for the DGR project design solution for the safety assessment of the disposal concept (framework contract)	05/2022–05/2026
SO2022-018-01	Study of the economic and socio-demographic benefits and risks of the DGR at the candidate sites for the development of the affected regions (implementation contract as part of RS SO2022-018)	06/2022–05/2024
SO2022-018-02	Update of the schedule of the life cycle of the DGR in connection with the acceptance of the terms of the Taxonomy (implementation contract as part of RS SO2022-018)	02/2023–06/2024
SO2022-018-07	Expert materials on the impacts of geological exploration work on the environment and public health at the candidate sites – "EIA GP Study" (implementation contract as part of RS SO2022-018)	09/2023–07/2024
SO2022-018-08	Biological screening of sites (implementation contract as part of RS SO2022-018)	06/2023–01/2024
SO2022-018-09	Final siting of the surface areas at the candidate sites with the involvement of Local Working Groups (implementation contract as part of RS SO2022-018)	09/2023–12/2025
SO2022-035	Mock Up Josef Dismantling	08/2022–08/2024

Contract no.	Project name	Duration
SO2023-008	In-situ determination of stress in Bukov URF II	03/2023–05/2027
SO2023-008	Contour blasting work	03/2023–12/2024
SO2023-030	Hydrogeological monitoring of surface, underground and mine water in the Bukov URF	06/2023–12/2024
SO2023-058	Pore pressure monitoring in Bukov URF II	01/2024–01/2027
TK01030031	Engineered barrier 200°C (TAČR project)	06/2018–12/2025
	COST EUROMIC	9/2023–9/2025
Grant No. 847593	EU programme EURAD (European Joint Programme on Radioactive Waste Management), EU project	06/2019–05/2024

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