Technical report 644/2022/ENGrev.1

Design of the Czech concept for the buffer, backfill, plugs, and sealing of disposal chambers for other RAW; the sealing of other underground spaces and construction elements

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Prague, 2023

SÚRAO

REPORT NAME: Design of the Czech concept for the buffer, backfill, plugs, and sealing of disposal chambers for other RAW; the sealing of other underground spaces and construction elements

PROJECT NAME: Backfill materials and other engineered components of the DGR

PROJECT IDENTIFICATION: Final report on subtask 5

CONTRACT NUMBER: SO 2020-092

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BIBLIOGRAPHIC RECORD: SVOBODA, J, ŠŤÁSTKA, J., VAŠÍČEK, R., ŠPINKA, O., BUREŠ, P., POSPÍŠKOVÁ, I., VOZÁR, M., KRAJŇÁK, M., ŠACHLOVÁ, Š., VEČERNÍK, P., ZUNA M., HAVLOVÁ, V., STIBLÍKOVÁ, P., ČERNÁ, K., HLAVÁČKOVÁ, V. (2022), Czech conceptual design of the buffer, backfill, plugs and chamber backfill for RAW, other backfills and structural elements, TZ644/2022/ENGrev.1, SÚRAO, Prague.

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Revision sheet:

Page/ chapter	Description of a change	Date	Author	Approved by
75	WDP dimensions correction	6.11.2023	Svoboda	

Contents

List of annexes

List of abbreviations

± *L*	confidence interval of the Student's distribution at a significance level α = 0.05.
AL	annealing loss
AVG	average
BCV	Černý vrch bentonite delivered to SURAO in 2017
c	specific heat capacity
CEC	cation exchange capacity
CEC_sum	sum of exchangeable cations
Ctot	total carbon content
d	diameter
DGR	deep geological repository
DuSO	mine construction entity
EDZ	Excavation Damaged/disturbed Zone
h	height
HLW	high-level waste
LPC	low pH concrete
LPM	low pH mortar
MP	methodological instruction
MSV	multi service vehicle
NA	not analysed
NNS	new nuclear sources
NPP	nuclear power plant
NRTM	New Austrian tunnelling method
OTSKP	Industry classification of construction structures and work
PP	polypropylene
RAW	radioactive waste
SI	swell index
SNF	spent nuclear fuel
SSA_EGME	total specific surface area
Stot	total sulphur content
SUM	summation
TBM	tunnel boring machine
VVER	water-water power reactor
w	moisture (weight)
WDP	waste disposal package
λ	thermal conductivity coefficient
ρ_d	dry density

Explanation of terms

Backfill

One of the engineered barriers; it is composed of compacted bentonite and located in the loading corridor.

Bentonite

Bentonite is a residual, non-displaced, clayey rock that is formed via the mechanical and chemical weathering of the parent rock (in an alkaline environment), i.e. mainly volcanic tuffs and tuffites and, to a lesser extent, andesites, rhyolites, basalts and other predominantly Tertiary rocks. Bentonite has a high content of clay minerals, predominantly montmorillonite, which is the main carrier of the characteristic properties of bentonite – its high sorption capacity, i.e. its high cation exchange capacity, swelling ability and plasticity and very low permeability. The other important components of bentonite consist of beidellite, kaolinite and illite.

Safety function

The safety function comprises the parts of the system, structures, components and other elements of a nuclear facility that are significant in terms of ensuring the nuclear safety of the facility.

Concrete

A building material that is created via the mixing of cement, fine and coarse aggregate, water and various admixtures and additives that serve to improve its properties.

Buffer

The buffer comprises an engineered barrier made of compacted bentonite that is placed in the disposal borehole so as to surround the WDP.

Spacer block

The spacer block, one of the engineered barriers, consists of compacted bentonite with the same material parameters as the buffer. It is positioned in the disposal borehole so as to ensure the required distance between the individual WDPs (H – system) or to separate the buffer from the backfill and to stabilise its position (V – system).

Waste disposal package (WDP)

In the context of this report, the WDP refers to the container used for the disposal of RAW other than spent nuclear fuel (SNF).

Dry density (ρ_d)

The dry density is the ratio of the mass of the solid phase to the total volume of a sample.

Construction entity

A construction entity is a spatially integrated or technically independent part of the DGR that fulfils a defined, targeted function.

Abstrakt

Tato zpráva je závěrečnou zprávou Dílčího úkolu 5 (DÚ05) zakázky SÚRAO „Výplně a ostatní inženýrské komponenty HÚ".

Zpráva obsahuje návrh českého koncepčního řešení bufferu, backfillu, zátek, výplní komor ostatních RAO, ostatních výplní a konstrukčních prvků.

Popis koncepčního řešení je organizován dle jednotlivých komponent navrženého řešení. Každá komponenta je nejprve stručně přestavena a dále pak detailně popsána – je popsaná její geometrie, použité materiály, umístění a použitelnost v úložišti, postup její přípravy a výstavby. V případě, že řešení má více variant jsou tyto varianty popsány. Součástí popisu komponent je také odhad ceny každé komponenty (v jednotkových cenách).

Klíčová slova

Hlubinné úložiště, konstrukční prvky, chemie, mineralogie, mechanika, mikrobiologie, provozní bezpečnost, dlouhodobá bezpečnost, bentonit, beton, zátka, buffer, backfill, výplně.

Abstract

This report comprises the final report concerning Subtask 5 (DÚ05) of the SÚRAO-commissioned "Backfill materials and other engineered components of the DGR" contract.

The report presents the conceptual design of the buffer, backfill, plugs and backfill for the RAW chambers and other backfill and structural elements.

The conceptual design consists of several distinct components. Brief overviews of each component are provided, followed by detailed descriptions (geometry, material specifications, location, intended use, terms of use, technology and the procedure for preparation and construction). Alternative options are presented where applicable. A cost estimate in unit prices is provided for each of the components.

Keywords

Deep geological repository (DGR), DGR components, chemistry, mineralogy, microbiology, operational safety, long-term safety, bentonite, concrete, plug, buffer, backfill.

1 Introduction

This report presents the conceptual design of backfill materials and other engineered components of the DGR. The conceptual design follows on from previous project design solutions (TZ 134/2017, Grünwald et al., 2018) and considers the previously obtained results of the Backfill project (TZ 616/2022, Večerník et al., 2022).

The design took into account safety, technical and economic aspects and currently valid legislation.

This initial version of the conceptual design will serve as one of the inputs for the safety calculation and the thermo-technical calculations, as well as for the preparation of the R&D programme and the DGR project as a whole. It is expected that the conceptual design will be regularly updated based on the outcomes of the continuous assessment of the concept.

1.1 Technical specification

The technical specification of the contract states: *The aim of this task is the proposal of the design of the basic technical solutions for the buffer, backfill and plugs, backfill for the disposal chambers for other (non-SNF) radioactive waste and the backfilling of the remaining underground spaces and structural elements of the Czech DGR and to suggest potential alternatives. The basic and potential alternative conceptual designs must contain:*

- *A description of the entire barrier/element – geometry and placement method and a description of the properties relevant to the DGR*
- *The material – the type of bentonite/concrete/mixture, etc., with a description of its properties as relevant to the DGR (e.g. smectite content, accessory mineral content, etc.)*
- *The components that will make up the barrier and description of their conditions (dimensions, moisture content and dry density) and the properties relevant to the DGR (e.g. hydraulic conductivity, swelling pressure, thermal conductivity, etc.)*
- *A basic description of the technology required for the production and placement of the barrier and the various components*
- *An estimation of the prices of all the components*

Output: *a report (in both Czech and English)*

1.2 Structure of the report

The report is divided into the following main chapters:

- The second chapter provides a brief description of the various features of the underground part of the DGR and the basic allocation of the backfill components.
- The third chapter provides a description of the materials (and the properties thereof) of the various components included in the conceptual design.
- The fourth chapter presents the assumptions included in the conceptual design.
- The fifth chapter presents the designs of the various components considered. A brief overview is provided of each of the components followed by a detailed description and valuation. The calculation applied for the valuation of the components is described in the electronic annex to the report.

2 Description of the DGR and its division into construction entities

The DGR will provide for the permanent disposal of SNF and RAW that is unacceptable for disposal in existing surface and near-surface disposal facilities and will consist of both underground and surface areas. While the surface area of the DGR will serve for the reception and preparation of SNF and other RAW for disposal, the underground complex of the DGR will serve mainly for the transport of the waste to the disposal areas and for disposal itself.

The disposal areas and the access corridors will be excavated in defined potentially usable rock blocks. The technical infrastructure of the underground part of the DGR will be located as near as possible to these blocks. The disposal areas will be located at a minimum depth of 500 m below the earth's surface. The disposal concept currently envisages the layout of the DGR in terms of one of the following options:

- **horizontal SNF disposal;**
- **vertical SNF disposal.**

These two options can be further divided into sub-options according to the concept for the preferred methods of excavation of the various underground components.

Concerning the rock excavation method, the following two approaches are being considered:

- The **mechanised excavation method** using full-profile excavation machines – mainly the hard rock TBM approach.
- The **conventional excavation method** – cyclical mining, which mainly employs blasting techniques (the NRTM or "Drill & Blast" methods).

The design approach to each of the disposal methods includes the use of these two preferred excavation methods. The resulting 4 layout options for the underground area of the DGR are presented schematically in annexes to (Butovič et al., 2020; Špinka et al., 2020a, 2020b; Zahradník et al., 2020).

The WDP with SNF disposal concept will exert a direct effect on the overall size and layout of the DGR. The horizontal disposal approach will have different spatial requirements concerning the size and layout of the disposal spaces to the vertical disposal approach.

The division of the underground part of the DGR into its various components according to (Butovič et al., 2020; Špinka et al., 2020a, 2020b; Zahradník et al., 2020) is shown in Tab. 1.

Tab. 1 Conceptual design components concerning the mining-related construction entities of the DGR

<table>
<tr><th>MINE CONSTRUCTION ENTITY NO.</th><th>CONSTRUCTION ENTITY</th><th>COMPONENT[1]</th></tr>
<tr><td>DuSO 01</td><td>UNLOADING TUNNEL</td><td rowspan="3">VY 04 Backfilling of space in the disposal horizon
VY 05 Backfilling of space above the disposal horizon
VY 06.05 Plug – pressure and sealing plug (separation of places with inflow/fractures),
VY07* Other structural elements</td></tr>
<tr><td>DuSO 02</td><td>LOADING TUNNEL</td></tr>
<tr><td>DuSO 03</td><td>INTAKE SHAFT</td></tr>
<tr><td>DuSO 04</td><td>RAW AND SNF PREPARATION</td><td>VY 05 Backfilling of spaces above the disposal horizon
VY 06.06 Plug – DGR sealing plug (loading and unloading tunnels, intake shaft),
VY 07* Other structural elements</td></tr>
<tr><td>DuSO 05</td><td>MAIN CORRIDORS</td><td rowspan="3">VY 04 Backfilling of space in the disposal horizon
VY 06.03 Plug – RAW chamber operational plug,
VY 07* Other structural elements</td></tr>
<tr><td>DuSO 06</td><td>CONNECTING CORRIDORS EXCAVATION SECTION</td></tr>
<tr><td>DuSO 07</td><td>CONNECTING CORRIDORS DISPOSAL SECTION</td></tr>
<tr><td>DuSO 08</td><td>LOADING CORRIDORS</td><td>VY 02 Loading corridor backfill
VY 06.02 Plug - loading corridor operational plug</td></tr>
<tr><td>DuSO 09</td><td>DISPOSAL BOREHOLES</td><td>VY 01 Disposal borehole buffer,
VY 06.01 Plug - horizontal disposal borehole operational plug</td></tr>
<tr><td>DuSO 10</td><td>SNF WDPs INSPECTION AND TRANSFER SECTION</td><td rowspan="2">VY 03 RAW chamber backfill,
VY 06.03 Plug – RAW chamber operational plug,
VY 07* Other structural elements</td></tr>
<tr><td>DuSO 11</td><td>RAW DISPOSAL CHAMBERS</td></tr>
<tr><td>DuSO 12</td><td>CONFIRMATION LABORATORY</td><td>VY 04 Backfilling of space in the disposal horizon
VY 06.01 Plug - horizontal disposal borehole operational plug
VY 06.02 Plug - loading corridor operational plug
VY 06.03 Plug – RAW chamber operational plug,</td></tr>
</table>

[1] The components marked with * must be assessed for use in specific locations from the point of view of the long-term safety of the DGR.

MINE CONSTRUCTION ENTITY NO.	CONSTRUCTION ENTITY	COMPONENT[1]
DuSO 13	FILLING STATION WITH SUMP	VY 04, Backfilling of space in the disposal horizon VY 06.04 Plug – disposal horizon operational plug, VY 07* Other structural elements
DuSO 14	ELECTRICAL SUBSTATION – EXCAVATION SECTION	
DuSO 15	ELECTRICAL SUBSTATION – DISPOSAL SECTION	
DuSO 16	PERSONNEL ASSEMBLY AREA, FIRST AID STATION AND TESTING ROOM	
DuSO 17	MACHINERY REPAIR AND MAINTENANCE WORKSHOPS	
DuSO 18	SPARE PARTS STOREROOM	
DuSO 19	LUBRICANTS STOREROOM, WASHING AND MAINTENANCE SECTION	
DuSO 20	SEDIMENTATION TANK	
DuSO 21	EXPLOSIVES STOREROOM	
DuSO 22	FIRE EQUIPMENT STOREROOM	

The DGR concept envisages an underground complex with two levels (referred to as "horizons"), the division of which will be determined by the function of these horizons; however, at this stage it is not yet possible to determine the exact height levels of the two horizons.

1) **"Surface area"**

   This horizon refers to the surface area of the repository, which will house the operational building of the facility. The surface horizon and its immediate surroundings will also house the subsurface RAW and SNF preparation area as well as the waste transfer hub and the hot cell, etc.

   The surface is defined by a relative height level of ±0.000, which indicates the lowest point relative to the rock block. This reference level is used for determining the minimum height of the overburden of the DGR, i.e. 500 m and, *inter alia*, for the relative definition of the height level of the disposal horizons.

2) **"Disposal horizon for other RAW"**

   This RAW disposal horizon will be located at a depth of at least 250 m below the surface and at least 50 m above the SNF disposal horizon. This horizon will serve for the location of the chambers for the disposal of other (non-SNF) RAW (DuSO 11, in the above table); it is expected that these chambers will be connected via a connecting corridor to the loading tunnel. It is also expected that one of these chambers will be used temporarily to house the confirmation laboratory (DuSO 12). Both entities will be located in the potentially usable rock blocks area.

According to the division of the closure of the DGR in the form of separate sections according to depth in line with the 580/2022 report (Dohnálková et al., 2022), this RAW disposal horizon will form the middle horizon of the DGR at a depth of 200 to 500 m below the surface.

3) **"Disposal horizon for SNF"**

This horizon will host the sections allocated to the disposal of SNF, the technical equipment for excavation, the SNF disposal preparation section and the confirmation laboratory. The sections for the disposal of SNF will be located in the potentially usable rock blocks, while the DGR technical support facilities will be situated outside these blocks. A depth of 500 m below the surface has been defined as the highest level for the disposal of SNF. Due to the need for a slope that allows for the gravity-led drainage of the disposal horizon, the technical facilities, including the waste reception area and the pumping station will be located several tens of metres lower than the SNF disposal section. Currently, the DGR layout design differs according to various project variants and, thus, the height characteristics of the underground area also vary; however, the SNF disposal horizon is expected to be located at a depth of between 500 m and 530 m below the surface.

These horizons will be interconnected by a loading and an unloading tunnel and the intake shaft, and the mouths of these main mine workings will be located in the same part of the surface area, with the exception of the intake shaft. A diagram of the DGR is shown in Fig. 1.

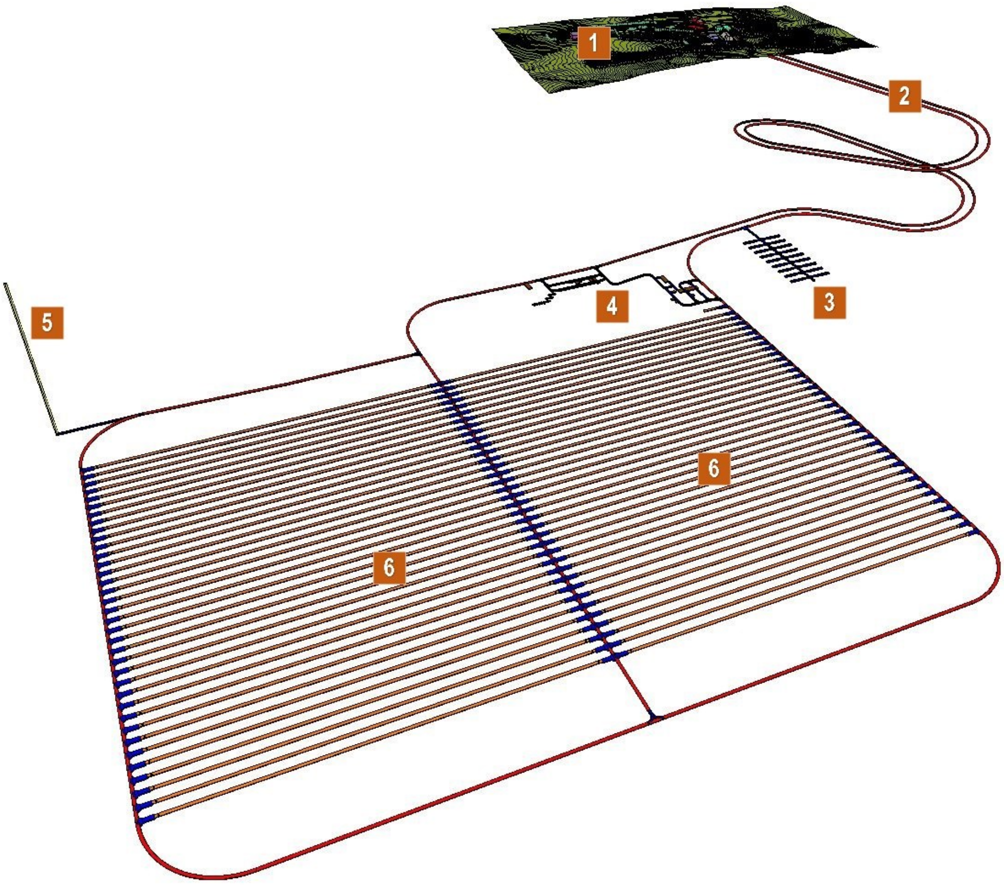

Fig. 1 Diagram of the DGR

Legend: 1 – Surface area, 2 – Loading and unloading tunnels, 3 – RAW disposal chambers, 4 – Underground area, 5 – Intake shaft, 6 – Disposal horizon loading corridor

The design parameters of selected mine-related entities, which are based on the 580/2022 report (Dohnálková et al., 2022), according mainly to the requirements of the DGR project design proposal (Grünwald et al., 2018), are listed in Tab. 2:

Tab. 2 Design parameters for selected mining-related construction entities

Ref. No.	Transverse dimensions [mm]	TBM excavation		Conventional excavation	
		Vertical disposal	Horizontal disposal	Vertical disposal	Horizontal disposal
DuSO 01 Unloading tunnel	Height	7,250	7,000	5,065	5,065
	Width	7,250	7,000	6,000	6,000
DuSO 02 Loading tunnel	Height	7,250	7,000	5,065	5,065
	Width	7,250	7,000	6,000	6,000
DuSO 05 Main corridors	Height	7,250	7,000	5,350	5,690
	Width	7,250	7,000	6,000	5,700
DuSO 08 Loading corridors	Height	7,250	-	6,700	-
	Width	7,250	-	4,000	-
DuSO 09 Disposal boreholes	Height	According to the WDP	2,200	-	-
	Width	1,650	2,200	-	-

3 Component materials

3.1 Bentonite

Bentonite is a residual, non-displaced clayey rock with high sorption capacity, cation exchange value and swelling and plasticity properties and very low permeability. The carriers of these properties comprise clay minerals, especially montmorillonite or beidellite. Bentonites are formed via the mechanical and chemical weathering of the parent rock (in an alkaline environment), mainly volcanic tuffs and tuffites and, to a lesser extent, andesites, rhyolites, basalts and other predominantly Tertiary rocks (Franče 1992). Bentonites also include montmorillonite clays, in which the lower content of montmorillonite significantly affects their properties and limits their potential for industrial use (Ryndová and Tvrdý 2020).

Industrially-mined and processed (homogenised) bentonite will be used as the backfill material. Natural untreated bentonite is not currently being considered for use in the DGR due to its inhomogeneities. However, it has not been ruled out that, in connection with the optimisation of the design of the DGR, natural bentonite will be considered for some of the components. If natural bentonite is used, its degree of homogenisation and the suitability of its properties will have to be confirmed.

It is assumed that the bentonite that will be used in the DGR will be of Czech origin, i.e. calcium-magnesium bentonite, a typical example of which is BCV bentonite extracted from the Černý vrch deposit. The main properties of BCV bentonite are summarised in Tab. 3 – Tab. 5. Tab. 6 shows the expected required properties of the bentonite according to the proposed conceptual design.

Tab. 3 Chemical composition of BCV bentonite (Šachlová et al., 2022). AVG – average, ± L – confidence interval, Ctot – total carbon content, Stot – total sulphur content, ND – not determined due to the limited amount of data available.

Chemical composition (wt %)	**BCV**	
	AVG	**± *L***
Al_2O_3	18.47	3.19
CaO	3.03	0.83
CO_2	2.45	0.89
Fe_2O_3	13.21	1.03
FeO	0.15	ND
K_2O	1.02	0.39
MgO	3.05	0.31
MnO	0.23	ND
Na_2O	0.35	0.08
SiO_2	54.31	2.42
TiO_2	3.24	0.72
SO_3	0.29	0.36
Ctot	0.47	0.33
Stot	0.01	-

Tab. 4 Mineralogical composition of BCV bentonite (Šachlová et al., 2022). AVG – average, ± L – confidence interval, ND - not determined.

Mineral (wt %)	**BCV**	
	AVG	**± *L***
Smectite	65.7	6.9
Illite	2.3	2.2
Kaolinite	6.6	4.4
Silica	8.4	3.9
Amorphous phase	7.8	3.3
Calcite	1.2	1.0
Siderite	0.5	0.6
Goethite	4.6	4.0
Other	5.9	ND

Tab. 5 Basic geochemical and geotechnical parameters of BCV bentonite (Šachlová et al., 2022). AVG – average, ± L – confidence interval, CEC – cation exchange capacity, CEC_sum – sum of exchangeable cations, SSA_EGME – total specific surface, NA - not analysed.

Geochemical and geotechnical parameters	**BCV**	
	AVG	**± L**
CEC (meq/100 g)	60.92	1.82
CEC_sum (meq/100 g)	65.33	3.20
SSA_EGME (m^2/g)	485	125
Hydraulic conductivity (m/s)	$4.84.10^{-13}$ for ρ_d = 1.4 g/cm^3 $1.43.10^{-13}$ for ρ_d = 1.6 g/cm^3 $7.81.10^{-14}$ for ρ_d = 1.7 g/cm^3	$2.45.10^{-13}$ for ρ_d = 1.4 g/cm^3 $5.00.10^{-14}$ for ρ_d = 1.6 g/cm^3 $4.26.10^{-14}$ for ρ_d = 1.7 g/cm^3
Swelling pressure (MPa)	1.76 for ρ_d = 1.4 g/cm^3 6.87 for ρ_d = 1.6 g/cm^3 13.56 for ρ_d = 1.7 g/cm^3	0.83 for ρ_d = 1.4 g/cm^3 3.24 for ρ_d = 1.6 g/cm^3 6.40 for ρ_d = 1.7 g/cm^3
Swell index (ml/2g)	7.8	0.2
Liquid limit (%)	138	2.69
Specific density (g/cm^3)	2.758	NA
Compressive strength (MPa)	4.2 for ρ_d = 1.5 g/cm^3	NA
Thermal conductivity (W/m.K) for w = 12%	0.445 for ρ_d = 1.4 g/cm^3 0.660 for ρ_d = 1.6 g/cm^3 0.750 for ρ_d = 1.7 g/cm^3	0.026 for ρ_d = 1.4 g/cm^3 0.039 for ρ_d = 1.6 g/cm^3 0.048 for ρ_d = 1.7 g/cm^3
Specific heat capacity (J/kg.K) for w = 12%	1,041 for ρ_d = 1.4 g/cm^3 963 for ρ_d = 1.6 g/cm^3 926 for ρ_d = 1.7 g/cm^3	29 for ρ_d = 1.4 g/cm^3 27 for ρ_d = 1.6 g/cm^3 26 for ρ_d = 1.7 g/cm^3
Plasticity limit (%)	45	NA
Thermal conductivity - shaken pellets (W/m.K) for w = 5%	0.3 for ρ_d = 1.4 g/cm^3	NA
Specific heat capacity - shaken pellets (J/kg.K) for w = 5%	1,010 for ρ_d = 1.4 g/cm^3	NA

The conceptual design envisages the use of two forms of bentonite as the backfill material:

- **Pelletised material** (after disposal, average ρ_d = 1,400 kg/m^3, pellets/fractions ρ_d >= 1,900 kg/m^3).
- **Blocks** (ρ_d = 1,700 kg/m^3).

The **pelletised material** consists of a mixture of compressed pellets and fractions with a suitable ρ_d and a suitable grain size curve so that the mixture can be emplaced without problems and the required average ρ_d of the backfill can be attained when emplaced. Typically, this mixture is produced using roller presses and the required grain size is obtained via sieving. In order to attain the highest possible ρ_d of the backfill from pellets/fractions, it is possible to apply the Fuller's numerical equation, which serves to determine the grain size curve with the optimal ratio of the various pellet/fraction grain diameters in order to ensure the maximum filling of the intergranular spaces of the material. The Fuller's calculation is able, therefore, to determine the theoretical grain line and allows for the design/production of a mixture of pellets/fractions for which the highest ρ_d can theoretically be considered. However, the resulting ρ_d of the backfill may still vary due to potential changes in the parameters (granularity) of the pellets/fractions during application. According to the basic testing approach described in the 489/2020 report (Šťástka et al., 2020), it can also be established that the maximum grain size of the pellets/fractions exerts an effect on the resulting ρ_d of the backfill. The larger the maximum grain, the larger the ρ_d of the backfill. In the case of the filling of so-called technological joints, various sources state that the maximum size (length) of the pellets/fractions should not exceed 1/3 of the width of the technological joint due to so-called "arching" in typically narrow technological joints. This condition, however, was stated in connection with the use of a material with the same grain size. Research on the filling of technological gaps has, to date, been rare in the Czech Republic and it will be necessary to address this issue in detail in the future. Nevertheless, for the needs of this project, sufficient information is available to determine the parameters necessary for the design of the component at this stage. The production moisture content of the material ranges from 3-6% (moisture weight; the 489/2020 report (Šťástka et al., 2020).

The **Blocks** comprise bentonite that has been compacted in a mould so as to attain the required shape and ρ_d. The production moisture content of the material ranges from 6-10% (moisture weight; the 533/2020 report).

Bentonites, including Czech bentonites, naturally contain microorganisms (Bengtsson et al., 2017; Černá et al., 2019; Mijnendonckx et al., 2021; Svensson et al., 2011; Taborowski et al., 2019). The development of bacterial communities is particularly problematic at the interface of the bentonite and other materials, for example the microbiologically influenced corrosion of steel or the deterioration of concrete. Moreover, microbial activity may also lead to structural changes in the bentonite itself (Kim et al., 2004; Kim 2012; Liu et al., 2012). The development of microbial activity in bentonite is facilitated by a structural disturbance or simply the presence of an interface between, for example, two blocks, which provides more living space for bacteria than does the homogeneous compacted material (Stroes-Gascoyne et al., 2002). Similarly, the development of microbial activity also occurs in places where the bentonite exhibits a lower bulk density. It is, therefore, important to prevent the occurrence of free spaces and inhomogeneities in the bulk density in the buffer material. On the other hand, the compaction of the bentonite to a high bulk density can significantly reduce the microbial activity (Černík et al., 2019; Grant 2004; Motamedi et al., 1996; Pedersen 2017; Pedersen et al., 2017) by ensuring that the microorganisms remain predominantly in the inactive spore state (Stroes-Gascoyne et al., 2007), with the corresponding lower germination rate (Pedersen 2017). The Finnish disposal concept suggests a dry bulk density for the buffer of between 1,400 and 1,600 kg/m^3 so as to prevent microbial activity (specifically, the dry bulk density (ρ_d) of the blocks above and below the WDP for the vertical disposal option should be 1,686 kg/m^3, surrounding the WDP 1,755 kg/m^3, and in the gaps filled with pellets 919 kg/m^3, which can be achieved, for example, by using pellets with a dry bulk density of > 1,600 kg/m^3; see the 575/2022 report, Kumpulainen et al., 2022). The German repository concept suggests a dry bulk density of approximately 2,000 kg/m^3 (so as to achieve a density of >2,200 kg/m^3 in the saturated state; Kumpulainen et al., 2022). The Canadian concept experimentally determined the dry bulk density of the buffer required to suppress the growth of bacteria and the germination of spores at 1600 kg/m^3 (density of the bentonite blocks: 1,700 kg/m^3 and pellets: 1,400 kg/m^3; Kumpulainen et al., 2022). The dry bulk density value required for the suppression of microbial activity has not yet been reliably determined for Czech bentonite. A further potentially important element in terms of safety concerns the content of organic substances that naturally occur in bentonite and which microorganisms are able to use to promote growth (Taborowski et al., 2019). The Finnish and Swedish disposal concepts determined the maximum content of carbon and sulphur in the buffer at 1 wt. % and sulphides at 0.5 wt. % (Kumpulainen et al., 2022) so as to limit the energy sources available for microbial activity. Concerning Czech iron-rich bentonite, in addition to determining the dry bulk density value that limits the microbial activity, it is also necessary to determine the effect of additional iron-containing minerals on the development of microbial activity and to verify the stability of the bentonite under microbial loading conditions.

Tab. 6 Proposed material properties for the conceptual design.

Property	Value	Justification	Notes
Bentonite type	Bentonite mined in the Czech Republic containing calcium-magnesium type smectite.	Local availability. Economic benefits. Not prone to colloid formation.	
Dry bulk density	According to use.	The dry bulk density of the bentonite component must be such that: • It ensures sufficient thermal conductivity (buffer). • It ensures the appropriate swelling capabilities (SI, swelling pressure). • It ensures sufficiently high impermeability (low hydraulic conductivity). • It limits the microbial activity (the value for Czech bentonite remains to be determined) and thus retards the WDP corrosion rate. • It provides for self-healing.	The dry bulk density limit value for limiting microbial activity has not yet been determined for Czech bentonite.
Mineralogical and chemical composition			
Smectite content	Maximum. The limit has not yet been set.	Carrier of swelling, self-healing, sorption and retardation properties.	
Content of minor and accessory minerals	Minimum.	Minerals may be, but are not necessarily, a source of nutrients for microbial activity. It is necessary to decide which of the additional minerals in Czech	Microbial activity can be reduced for even less suitable bentonites (in terms

Property	Value	Justification	Notes
	The limit has not yet been set.	bentonites may pose a risk from the point of view of microbial activity and then determine their maximum content. As a result of the dissolution of secondary and accessory minerals, changes occur in the composition of the pore solution, which may affect the stability and geochemical and geotechnical parameters of smectite.	of the amount of additional and accessory minerals) by exerting a higher dry density.
Total content of organic C	Minimum. The limit has not yet been set.	Source of nutrients for microbial activity.	Abroad - total organic carbon content (Ctot) < 1 wt. %. Posiva SKB (2017).
Total content of S	Minimum. The limit has not yet been set.	Source of nutrients for microbial activity.	Abroad - sulphur content (Stot) < 1 wt. %; < 0.5 wt. % for sulphides, Posiva SKB 2017, Kumpulainen et al. 2022).
Total content of Fe^{x+}	Minimum. The limit has not yet been set.	Source of nutrients for microbial activity.	Microbial activity can be reduced for even less suitable bentonites (in terms of the amount of additional and accessory minerals) by exerting a higher dry density.
Cation exchange capacity	Specific values have not yet been determined.	A property that determines the sorption/retention properties.	

Property	Value	Justification	Notes
Specific surface	Specific values have not yet been determined.	A property that determines the sorption/retention properties.	
Hydro-physical properties			
Hydraulic conductivity coefficient	<=10^{-11} m/s for ρ_d = 1,400 kg/m^3 <=10^{-12} m/s for ρ_d => 1,600 kg/m^3	Limitation of the transport of water and colloidal substances (diffusion as the primary process in the DGR). Limit: <=10^{-11} m/s for the backfill and other filling materials <=10^{-12} m/s for the buffer	
Swelling pressure	1-3 MPa for ρ_d = 1,400 kg/m^3 4-10 MPa for ρ_d = 1,600 kg/m^3 8-20 MPa for ρ_d = 1,700 kg/m^3	Limitation of mechanical damage to the WDP. Limitation of the transport of water and colloidal substances. Limitation of microbial activity. Ability to fill voids and to self-heal. Limit: <10 MPa (mean value) for the buffer as a whole due to the resistance of the WDP. The expected resistance of the WDP is 20 MPa, of which 5 MPa is allocated to the effects of pore pressure (water pressure) and 10 MPa to the impacts of the effective stress (swelling pressure); 5 MPa is the safety	The dimensions of the spacer block must be adjusted according to the specific values of the selected material. The value must be verified in terms of the spatial arrangement and the selected specific material so as not to endanger the integrity of the WDP.

Property	Value	Justification	Notes
		margin, to cover, *inter alia*, uncertainties concerning the design solution (e.g. dispersion in the bulk density and the swelling pressure of the barrier)	
Swell index	>= 4 ml/2g	Ability to fill voids and to self-heal.	Value to be verified.
Self-healing	Self-healing ability	Ability to restore its function after breakage/damage	
Moisture content	> 4% pellets (ρ_d => 1,900 kg/m^3) 10-20% blocks (ρ_d = 1,700 kg/m^3)	Guarantee of minimum thermal conductivity and workability.	
Liquid limit	w_l > 90%	Ability to fill voids and to self-heal. High plastic behaviour ability. Mechanical protection of the WDP.	Clay with extremely high plasticity (ČSN-EN 73 6133).
Porosity	Specific values have not yet been determined.	It affects the hydraulic conductivity coefficient, the transport of water and colloidal substances, the migration of radionuclides, the composition of the pore solution and the availability of nutrients for microbial activity.	Determination suitable for fully saturated bentonite.
Constrictivity	Specific values have not yet been determined.	It affects the hydraulic conductivity coefficient, the transport of water and colloidal substances and the migration of radionuclides.	Determination suitable for fully saturated bentonite.
Tortuosity	Specific values have not yet been determined.	It affects the hydraulic conductivity coefficient, the transport of water and colloidal substances and the migration of radionuclides.	Determination suitable for fully saturated bentonite.

Property	Value	Justification	Notes
Gas permeability	Specific gas permeability values have not yet been determined.	Gas accumulation may lead to breakthrough, the desaturation of the bentonite and the creation of preferential pathways.	
Mechanical properties			
Compressive strength	>3 MPa for ρ_d = 1,700 kg/m^3	Ensuring the stability of the location of the WDP in the buffer. Ability to resist swelling.	The value must be verified in terms of the spatial arrangement and the selected specific material.
Shear properties			
Internal friction angle	Specific values have not yet been determined.	Ensuring the stability of the location of the WDP in the buffer. The mechanical protection of the WDP. The ability to fill voids and to self-heal.	
Cohesion	Specific values have not yet been determined.		
Deformation properties			
E_{def}	Specific values have not yet been determined.	Spatial stability of the WDP and its mechanical protection. The ability to fill voids and to self-heal.	

Property	Value	Justification	Notes
Poisson number	Specific values have not yet been determined.		
Thermal properties			
Thermal conductivity (λ)	>0.2 W/m/K for ρ_d = 1,400 kg/m^3, w = 5% (buffer - joints, backfill) >0.3 W/m/K for ρ_d = 1,400 kg/m^3, w = 10% >0.5 W/m/K for ρ_d = 1,600 kg/m^3, w = 10% >0.6 W/m/K for ρ_d = 1,700 kg/m^3, w = 10% (buffer - blocks)	Guarantee of the removal of heat from the WDP.	The minimum value (together with the proposed geometry) must be verified via a numerical model of the propagation of heat in the DGR with respect to the temperature limit at the WDP/bentonite interface.
Specific heat capacity (c)	Not a requirement Typical value of c = 800-1,200 J/kg/K		
Thermal diffusivity	See λ, c a ρ_d. dif. = λ / (ρ * c)	See λ.	

3.2 Concrete

According to the 616/2022 report (Večerník et al., 2022), concrete comprises a construction material created by mixing cement, fine and coarse aggregate, water and admixtures and additives that serve to enhance its properties. In the case of classic concretes used in normal construction practice, a highly alkaline leachate with a pH value of > 12.5 is formed following contact with water. Such highly alkaline solutions degrade bentonite barriers; therefore, concretes are being developed with a reduced leachate pH (so-called low-pH concretes) so as to eliminate these negative effects. The pH values of the leachates of these concretes are mainly below 11.5.

The use of low-pH concretes is aimed at reducing the pH of the leachate so as to reduce their negative influence on the other DGR barrier materials, especially bentonite. While the exact pH value has not been defined, it is usually considered to be in the range 11.0-11.5. While the composition of the raw materials used in low-pH concretes is similar to that of ordinary concrete, the proportion of components that contain microstructural SiO_2 is enhanced. Mortar (LPM) and concrete (LPC) with low pH have been developed as part of previous SÚRAO-commissioned research projects. Their properties and composition are set out in the 369/2019 (Kratochvíle et al., 2019) and 415/2019 (Pernicová et al., 2019) reports. The composition of the concrete mixture defined in the latter report is shown in Tab. 7.

Tab. 7 Composition of the concrete mixture with a reduced leachate pH according to the 415/2019 report

Raw material	**Amount** (kg/m^3)
Dobříň aggregate	1,712
CEM I 42.5 R cement	140
Microsilica	179
Dětmarovice slag	32
Water	200
Plasticiser	7
Defoamer	1.75

The concrete structural elements in the DGR will not be intended to fulfil any long-term safety functions, and their gradual degradation is expected due mainly to the dissolution and leaching of the binding agent (binder) from the concrete. However, the aggregate used in the concrete mixture will remain more or less intact. No exact value has been determined to date for the proportion of aggregate; this calculation will be based on experience obtained in construction practice and, possibly, foreign and/or experimental data (e.g. the DOPAS project). Both fine and coarser aggregates are used, most often with a grain size of 0-16 mm (or 0-12 mm) in amounts of 1400 kg/m^3 of concrete (Dahlström 2009; Bosgiraud et al., 2014), 1600 kg/m^3 of concrete (Vogt et al., 2009; SKB TR-10-16; Grahm et al., 2015) or 1800 kg/m^3 of concrete (Holt and Koho, 2016). The application technology, i.e. spraying (shotcrete) or casting (monolithic concrete) is a critical factor in terms of the composition of the concrete.

In contrast to bentonite, concrete environments are inhospitable for the development of microbial activity (high pH, high temperature during the cement production process, increased temperature during the concrete hydration process, lack of water and nutrients, increased salt content). Nevertheless, bacteria do occur in concrete (Kiledal et al., 2021; Maresca et al., 2016) mainly due to human activity during preparation, as well as contamination from the cement and aggregate components. Thus, the development of bacterial communities in concrete is difficult to predict. Compared to ordinary concrete, LPC has a lower pH, which may lead to the earlier and more significant development of microbial activity, especially in environments that are rich in organisms (Mijnendonckx et al., 2018; Mijnendonckx et al., 2019b; Mijnendonckx et al., 2019a; Shrestha et al. al., 2022), i.e. on the contact of the LPC and the bentonite, the rock or the groundwater. The bio-deterioration process (i.e. the ageing and increased brittleness of the concrete) may occur at the contact between the concrete and the bentonite. On the other hand, the concrete will also affect the bentonite due to the increase in the pH of the bentonite via the alkaline leaching of the concrete, which could result in a decrease in the number of microorganisms; moreover, the development of microbial communities may be altered, which will lead to changes in the microbial activity in the bentonite (Taborowski and Pedersen, 2018; Shrestha et al., 2022). In addition, the concrete may contain compounds that exert an inhibitory effect on bacteria, e.g. calcium formate or calcium hydroxide (Morrier et al., 2003; Turick and Berry, 2016; Yamanaka et al., 2002). For more information on the interaction of concrete with other materials, see the 616/2022 report (Večerník et al., 2022). The mutual interaction of concretes and bentonite have not been sufficiently investigated under Czech conditions to date; thus, this issue should form the subject of future research.

3.2.1 Monolithic concrete

Monolithic concrete refers to concrete that is hardened in moulds (formwork, etc) at the site of construction. A typical example of this approach concerns the lining of tunnels and concrete plugs. Concerning the DGR, monolithic concrete will be used, *inter alia*, for the stabilisation backfilling of the RAW chambers.

3.2.1.1 Structural concrete

With regard to the requirements of the DGR, it is assumed that concrete will be used with a reduced leachate pH (low pH concrete) in the SNF disposal horizon. The composition of the concrete mixture will have to guarantee the minimisation of negative interactions with the other engineered barrier materials and satisfy the set compressive strength value and the other technical properties. The technical conditions are as follows:

- Workability and pumpability.
- Adhesion to the substrate.
- Long-term chemical stability.
- Resistance to the environment.
- Long service life
- Permeability.
- Ability to transfer loading after cracking.

The finally determined concrete mixture will be designed and/or provided by the finally selected contractor following approval from the project designer and, subsequently, the proposal will be submitted to the client for final approval.

The specification of the prescribed mixture per 1 m^3 will, generally, be required to contain the following information:

- The type, grade and amount of the cement.
- The type and amount of the aggregate with a documented grain line, the moisture content and the amount of leachable particles
- The type and amount of admixtures
- The type and amount of additives.
- The quantity of water – water coefficient
- The determination of the consistency before application.

A low pH concrete mixture has been developed in the Czech Republic by the Klokner Institute (Pernicová et al., 2019). In order to verify the reproducibility of the mixture at the industrial scale, its properties were verified using samples produced in a concrete plant (large-volume concrete production). The composition of the concrete mixture used in the large-scale production process is shown in Tab. 8.

Tab. 8 Composition of the low pH concrete mixture used for large-scale production (Pernicová et al., 2019)

Component	Amount
CEM I 42.5R cement	140 kg
Microsilica	179 kg
Dětmarovice slag	32 kg
Dobříň aggregate	1,712 kg
Plasticiser	7 kg
Defoamer	1.75 kg
Water	200 kg

3.2.1.2 Backfilling concrete

The RAW chamber backfilling concrete fulfils a critical safety function. The composition of the concrete will have to take into account the specific conditions of the selected site, especially the chemical composition of the groundwater.

Currently, self-compacting concrete with an extended hardening time is used for the stabilisation of the RAW disposal chambers at the Richard and Bratrství repositories.

When determining the properties of the concrete (cement backfilling) therefore, it is possible to start with the parameters of the concrete used to stabilise the chambers at the Richard and Bratrství repositories; however, as mentioned above, it will be necessary to take into account the specific conditions of the selected site for the DGR.

The following text provides a description of the preparation of the backfill concrete used at the Richard repository for illustrative purposes.

Cement with the following parameters is used in the preparation of the concrete mixture (MP.38):

- Degree of environmental influence due to chemical activity: XA1 and corrosion due to carbonation: XC2.
- Strength class of at least C 30/37.
- Exclusively blast furnace slag cement: types CEMIII/B or CEMIII/C.
- Sulphate resistant cement (SR), with a low hydration (LH) heat.
- Chloride content must correspond to class Cl 0.10.
- The filler must consist of silica sand and/or gravel. The rounding of gravel must be in accordance with category FI20, the maximum grain size must not exceed 10 mm.
- No powdered anhydrite, gypsum, dolomite or limestone must be added to the concrete mix.
- Water to cement ratio of less than 0.52, a cement content of at least 300 kg/m^3.
- Mineral additives can be added according to the relevant standards, as well as inert additives, provided that these substances do not act to deteriorate the quality of the concrete.
- It is possible to use dry industrially-produced concrete mixtures with the corresponding properties for the preparation of fresh concrete mixtures.

Requirements for the self-compacting of backfill concrete (MP.38):

a) Characteristic compressive strength of the concrete determined using test cubes according to ČSN EN 12390-3 after 28 days of ageing: min. 37 MPa.
b) Concrete seepage depth according to ČSN EN 12390-8: max. 75 mm for concrete structures with a thickness of at least 0.1 m.
c) Workability according to ČSN EN 12350-8, fluidity class SF2 (cake diameter: min. 660 mm during the slump flow test).
d) Processing time following delivery to the destination: min. 6 hours

This corresponds to the following composition of 1 m^3 of grouting concrete (Tab. 9).

Tab. 9 Composition of 1 cubic metre of grouting concrete (MP.38)

Component	Origin	Amount
Cement	CEM III/B 32.5 SV	410 kg
Filler	Power plant fly ash	180 kg
Aggregate	0/4	700 kg
	4/8	850 kg
Plasticiser	Stachement 2000	4.5 kg
	Stacheplast MV	2.0 kg
Water		200 kg

In the event that the concrete is expected to come into contact with the engineered barriers, the composition will have to be adjusted so that the resulting concrete has a reduced pH.

3.2.2 Shotcrete

The composition of the concrete mixture must generally guarantee a number of the properties required of the concrete, which have already been specified in detail in chapter 3.2.1 for monolithic[2] concrete, and of which the most important concerns the attainment of the prescribed course of compressive strength immediately following spraying and after 28 days. The technical conditions concern:

- Workability and pumpability.
- Resistance to the effects of aggressive (underground) water.
- Adhesion to the substrate.

Concerning permanent structures, it is necessary to determine:

- Lifespan
- Permeability
- Ability to transfer loading following cracking.
- Long-term chemical stability.
- Resistance to chlorides.

The finally determined concrete mixture will be designed and/or provided by the finally selected contractor following approval from the project designer and, subsequently, the proposal will be submitted to the client for final approval.

The specification of the prescribed mixture per 1 m^3 will be required to contain the following information:

- Type, grade and amount of cement.
- Type and amount of aggregate with a documented grain line, moisture content and amount of leachable particles
- Type and amount of additives
- Amount of water – water coefficient (only for the wet mixture).
- Determination of consistency before application (only for the wet mixture).
- Type and amount of additives.
- Type and content of fibres.

Taking into account the numerous disadvantages of dry spraying, e.g., according to (Hilar et al., 2008), high levels of dust, higher fall rate, lower quality, etc., it is suggested that the **wet spraying method** be applied.

Concerning its use in the DGR, it is assumed that concrete of at least class SB 30 will be used. The concrete will have a reduced pH for those components that form part of the engineered barrier system.

The approximate composition of the concrete mixture for the spraying of 1 m^3 via the wet method according to (Hilar et al., 2008) is shown in Tab. 10.

[2] The parameters and composition of monolithic concrete cited in the chapter may not correspond to the required values when applied via the spraying method, especially those properties related to the technology of the application of the concrete mixture. For example, a prescribed hardening curve.

Tab. 10 Approximate composition of a concrete mixture for the spraying of 1 cubic metre via the wet method

Component	Amount
CEM I 42.5 R cement	430 kg
0–4 mm aggregate	1,025 kg
4–8 mm aggregate	645 kg
Plasticiser	4 kg
Accelerating additive solution with water (added to the nozzle)	Approx. 185 kg
Accelerating additive	5.5 to 8% by the weight of cement

3.2.3 Prefabricates

The term prefabricates generally refers to building components that are made from concrete, and which were specified in detail in the introductory part of this chapter.

Following the closure of the DGR, it is assumed that the following types of prefabricates will remain in the facility:

- Segmental linings.
- Formwork blocks.

Formwork blocks will be necessary for the construction of the plugs (the temporary retention of the bentonite filling material) and for the backfilling of the RAW chambers (the separation of sections of the chambers during their section-by-section backfilling using a cement-based backfill material).

Segmental lining will be required in areas of the DGR with fracture networks. However, leaving the lining in place (and the extent thereof) will have to be assessed from the point of view of the long-term safety of the DGR.

The hollow formwork blocks, referred to as hidden or lost formwork, will be made of vibro-pressed high-strength concrete with a reduced pH level. The interaction of pressure and vibration during the production process guarantees a high degree of strength. Their high density ensures that they exhibit excellent parameters in terms of the following mechanical-physical properties:

- Compressive strength.
- Fire resistance.
- Optimal surface roughness.
- High precision.
- Minimal absorbency.

3.3 Aggregate

According to Svoboda et al. (2013), aggregate refers to granular inorganic materials, of natural or artificial origin, that are intended for construction purposes.

Natural aggregates comprise aggregates of inorganic origin, which can be divided into quarried and crushed, depending on the extraction method and subsequent treatment.

Mined aggregate is of glacial origin or is extracted from river sediments. It is formed by the natural breakdown of rock and is mined from water courses and alluvium layers. It usually exhibits a rounded grain shape with a surface that has been smoothed naturally during the transport of the weathered rock.

Crushed aggregate is characterised by an irregular grain shape, sharp edges and rough surfaces. It is obtained via the artificial crushing of large pieces of natural rock and its subsequent classification.

Artificial aggregate is defined as aggregate of inorganic origin that has been subjected to thermal or other process. It is produced from industrial waste (ash, slag, etc.) or from modified rock materials (ceramsite, expanded perlite, siopor).

Recycled aggregates, which are becoming increasingly popular, comprise artificial aggregates. The relevant industrial standard states that it comprises an aggregate of inorganic origin that was previously used for construction purposes, usually crushed bricks and concrete.

Concerning the DGR project, it is assumed that aggregate will be used in combination with suitable binders primarily as a filler for the preparation of mortars and concretes and, subsequently, as a filler in mixtures with bentonite.

The requirements concerning the aggregate are as follows:

- Granularity – specified only in relation to its use in concrete materials (see chapter 3.2). Its use for the backfilling of the space above the disposal horizon at medium depth (-500 to -200 m) and subsurface areas (up to -200 m) has not yet been decided.
- Shape index – not yet determined.
- Shell content - not yet determined.
- Resistance to freezing and thawing – although this aspect has not yet been determined, it will only be relevant concerning its use in the concrete lining of the main mine workings.
- Chemical stability – the aggregate should have a minimum content of reactive SiO_2 and sulphides in order to ensure its stability in contact with the bentonite and groundwater (Liu et al., 2003; Mata Mena, 2005; Cloet et al., 2017). The specific requirements have not yet been determined.
- Strength – not yet determined.
- Durability – not yet determined.
- Absorbency - not yet determined.
- Impact resistance – not yet determined.

From the point of view of the properties of the concrete mixture and the properties and durability of the resulting concrete, it is important that the aggregate does not contain harmful substances that, when in contact with cement sealants, exert an adverse effect on the solidification and hardening of the cement sealant resulting in internal stress and the breakdown of the structure of the hardened concrete and a reduction in the degree of the cohesion of the concrete to steel.

Concerning the DGR, it is assumed that modified rubble obtained from the construction of the DGR itself will serve as the primary source of the aggregate. This will reduce the amount of materials of non-local origin. With respect to determining the best location for the DGR (Vondrovic et al., 2020), it will be possible to test a mixture of Czech bentonite and the rock that is typical for the selected site. This is the only way in which to determine the requirements of the aggregate in terms of filling the spaces above the disposal horizon.

4 Prerequisites for the components

The approach to the conceptual design concerns ensuring that the various components are able to fulfil the required functions in the DGR.

4.1 Design considerations

The following considerations were taken into account during the design process:

A) Safety considerations

- The materials used in the various components and their geometry must be compatible with the other elements of the DGR, especially the engineered barrier and (primarily) the WDP, so that there is no negative mutual influence that would lead to a reduction in their lifespans. Note: Compatibility also depends on the position of the components/subcomponents in the DGR and their geometry (e.g. whether the component is in direct contact with the barriers or whether a part of the component could create preferential pathways for water following the degradation of the component materials). For more details, see the 616/2022 report (Večerník et al., 2022).
- The materials used must have such a lifespan that they fulfil the required functions for the duration of the safety requirement.

B) Technical considerations

- Since the selected materials will be tested experimentally so as to ensure that they meet the defined safety requirements, they must be commonly available in the market. Moreover, there must be no risk that no manufacturer or supplier will be available at the time of the required use.
- The materials must be easily available in the required quantity and at the required quality, without any above-standard requirements for special technology or for the development of new technologies (the economic point of view). The use of proven processing and modification technologies, concerning which it is possible to set quality requirements based on previous results, will be advantageous.

C) Economic considerations

- The costs of the materials used and the related production/treatment technology and final installation should respect the requirement to ensure safety at a reasonable cost.

D) Legislation

- The various aspects will, naturally, have to be addressed in accordance with the applicable legislation. According to the DGR design solution proposed by (Grünwald et al., 2018), the issue of the disposal of radioactive and other waste in underground spaces from the construction point of view are currently addressed (November 2022) in section 34, paragraph 1b) of Act ČNR (Czech National Council) No. 44/1988 Coll., as amended, on special intervention into the earth's crust, which according to section 2 f) of Act ČNR No. 61/1988 Coll., on mining activities, explosives and the state mining administration, as amended, comprises a mining-related activity.

4.2 Unit prices used to value the components

The prices for commercially available materials and components (e.g. concrete, equipment, rock bolts, etc.) considered in this report are based on 2022 prices quoted in the classification of building structures and construction work (OTSKP, 2022).

The estimation of the prices of the cement backfilling materials was based on the expert estimation approach and experience obtained from similar construction projects (the Richard and Bratrství repositories) at 2022 price levels. The unit price comprises the price for the material including its preparation and installation; this value was set at 11,400 CZK/m^3.

The estimation of the price of bentonite-based backfilling materials was based on the price stated in the 134/2017 report (Grünwald et al., 2018), which was increased by the inflation rate over the period 2018-2022. The current price was determined as follows for various densities of the dry matter of the backfilling; for example, report 134/2017 quotes the price of the bentonite material, including handling, as 10,017 CZK/m^3 for a material with ρ_d = 1600 kg/m^3. This corresponds to 6.26 CZK/kg of the dry matter. When considering cumulative inflation for the period 2018-2022 in the amount of 1.294 (see Tab. 11), the price at the end of 2022 equated to 8.1 CZK/kg of the dry matter. This price takes into account the difficulty of the preparation and installation of the material for the backfilling of the disposal boreholes (Tab. 12), which will comprise primarily bentonite blocks. The installation of other, pellet based, backfilling is likely to be cheaper than compressed blocks due to its easier handling/installation and cheaper production process. However, it is currently not possible to determine the price difference.

Tab. 11 Inflation rates (source: Czech Statistical Office (CZSO) 10.11.2022)

Year	Inflation [%]	Price increase	Cumulative price increase
2018	2.1	1.021	1.021
2019	2.8	1.028	1.0496
2020	3.2	1.032	1.0832
2021	3.8	1.038	1.1243
2022[3]	15.1	1.151	**1.2941**

Tab. 12 Unit price of the bentonite filling for the disposal boreholes

Bentonite dry density [kg/m^3]	Price [CZK/m^3]
1,400	11,343
1,600	12,963
1,700	13,773

[3] The rate of inflation expressed as the increase in the consumer price index compared to the same month of the previous year (October, CZSO 10.11.2022)

4.3 Procedure in the event of unsatisfactory conditions for the component (remedial action)

In the event of unsatisfactory conditions for the component, local remediation, i.e. filling and closure will be conducted applying the same procedure as for the original selected variant of the component for the respective environment.

In the case of the disposal boreholes, chambers and loading corridors, should such issues arise they will not be used for the disposal of radioactive waste.

5 Design of the various components

The conceptual design concerning the backfilling of the DGR was divided into 7 distinct components (Tab. 13), which were further divided into variants and subvariants

The division into variants was based primarily on the specific purpose and expected geometry of the respective component. The division into subvariants was then based primarily on the respective technical/material design proposal.

Tab. 13 List of components

Ref. no.	Component	Component variants	Subvariants
VY 01	Disposal borehole backfill	VY 01.01 Disposal borehole backfill – horizontal disposal borehole with a diameter of 2.2 m	01 Blocks (entire profile) + joint filling (pellets, granulate) (preferred subvariant) 02 Blocks (bed) + pelletised material 03 Pelletised material in the entire profile
		VY 01.02 Disposal borehole backfill – horizontal disposal borehole with a diameter of 1.7 m	01 Blocks (entire profile) + joint filling (pellets, granulate) (preferred subvariant) 02 Blocks (bed) + pelletised material 03 Pelletised material in the entire profile
		VY 01.03 Disposal borehole backfill (buffer) – vertical disposal borehole	01 Blocks + pelletised material (preferred subvariant) 02 Pelletised material
VY 02	Backfilling of the loading corridor	VY 02.01 Backfilling of the loading corridor	01 Backfilling of the loading corridor – TBM excavation 02 Backfilling of the loading corridor – NRTM excavation
VY 03	Backfilling of the RAW chambers	VY 03.01 Backfilling of the RAW chambers – whole chamber	01 Cement backfilling 02 Bentonite backfilling
		VY 03.02 Backfilling of the RAW chambers – section-by-section filling of the chambers	01 Cement backfilling 02 Bentonite backfilling

Ref. no.	Component	Component variants	Subvariants
VY 04	Backfilling of the spaces in the disposal horizon	VY 04.01 Backfilling of the spaces in the disposal horizon	01 Pelletised material
VY 05	Backfilling of the spaces above the disposal horizon	VY 05.01 Backfilling of the spaces above the disposal horizon (medium depth)	01 Bentonite 02 Bentonite and aggregate mixture (preferred variant)
		VY 05.02 Backfilling of the spaces above the disposal horizon (subsurface)	01 Backfilling of the unloading and loading tunnels 02 Backfilling of the intake shaft
VY 06	Plugs	VY 06.01 Plug – Operational plug for horizontal disposal boreholes	01 Operational plug made of fibre shotcrete 02 Operational plug made of monolithic reinforced/fibre-reinforced concrete
		VY 06.02 Plug – Operational plug for the loading corridor	01 Operational plug made of fibre shotcrete 02 Operational plug made of monolithic reinforced/fibre-reinforced concrete
		VY 06.03 Plug – Operational plug for the RAW disposal chambers	01 Operational plug made of fibre shotcrete 02 Operational plug made of monolithic reinforced/fibre-reinforced concrete
		VY 06.04 Plug – Operational plug for the disposal horizon	01 Operational plug made of fibre shotcrete 02 Operational plug made of monolithic reinforced/fibre-reinforced concrete

Ref. no.	Component	Component variants	Subvariants
		VY 06.05 Plug - Pressure and sealing plug (separation of water inflows/fracture zones)	01 Operational plug made of fibre shotcrete 02 Operational plug made of monolithic reinforced /fibre-reinforced concrete
		VY 06.06 Plug – DGR closure plugs (inclined main tunnels, shaft plug)	01 Portal closure plug for the inclined main tunnels 02 Closure plug for the intake shaft
VY 07	Other structural elements	VY 07 Other structural elements	01 Reinforcement 02 Rock bolts 03 Micropiles 04 Grouting 05 Lining and lining components

5.1 VY 01.01 Disposal borehole backfill – horizontal disposal borehole with a diameter of 2.2 m

5.1.1 Component details

Name	Disposal borehole backfilling (buffer) - horizontal disposal borehole
Description	Backfilling of the disposal borehole – horizontal WDP disposal method
Location in the DGR	Disposal borehole
Applicability conditions	• Clean excavation without significant disturbances or active water inflows (the exact criteria will be specified in the future) • No materials must be introduced into the disposal borehole or loading corridor (e.g. remnants of linings, ground levelling, etc.)
Subvariants	01 Blocks (entire profile) + joint filling (pellets, granulate) (preferred subvariant) 02 Blocks (bed) + pelletised material 03 Pelletised material in the entire profile
Material	Bentonite
Subcomponents	01 Bed for the WDP (backfilling beneath the WDP) 02 Main backfill (excl. the bed) and in the spacer block 03 Ground levelling layer 04 Filling of the technical joints Note: Closure of the boreholes, see VY 06.01 Operational plug for horizontal disposal boreholes
Production/preparation technology	Industrially processed bentonite in the form of pelletised material and blocks.
Installation/construction technology	01 Assemblage from prefabricates (compressed parts) 02 Backfilling pneumatically or by mechanical conveyor (screw conveyor, gravity transport, vibrating conveyor), on-site compaction

5.1.2 Component requirements

5.1.2.1 External requirements and specifications

5.1.2.1.1 Requirements from the 580/2022 report

Technical report 580/2022 (Dohnálková et al., 2022) sets out the following requirements for the backfilling of the disposal boreholes and related components.

Backfilling (buffer and spacer block):

- ρ_d of the whole of the barrier: 1,600 kg/m^3
- Moisture content following the emplacement of the buffer: at least such that it allows for the sufficient removal of heat from the WDP, the surface of which must not be more than 95°C

Buffer

- Width: 643 mm
- Thickness in front of the WDP: 350 mm
- Thickness behind the WDP: 350 mm

Spacer block

- Width: 2,200 mm
- Length: 500 mm

Borehole

- Diameter of the disposal borehole: **2,200 mm** (for all types of SNF), (Grünwald et al., 2018)
- The horizontal axial distance between the WDPs in the borehole depends on the type of fuel (Grünwald et al., 2018[4]): for VVER 440 = 7,750 mm, VVER 1000 = 22,000 mm and NNS more than 45,000 mm.
- The axial distance between the boreholes does not depend on the type of fuel (Grünwald et al., 2018[5]): 35,000 mm.
- Length of the disposal borehole: 290,000 mm (Grünwald et al., 2018)
- Total number of required disposal boreholes: 404 (Grünwald et al., 2018).
- Zone affected by excavation around the disposal boreholes: 350 mm (Grünwald et al., 2018).

WDP

Proposed WDP parameters:
- Maximum temperature on the surface of the WDP: 95°C
- Specification of the WDP according to the SNF:
    - VVER 440: h = 3,970 mm, d = 914 mm
    - VVER 1000: h = 5,205 mm, d = 914 mm
    - NNS: not yet determined
- Proposed ambient pressure on the WDP: up to 20 MPa

[4] The horizontal axial distances between the WDPs in the wells rely on the assumption that the SNF has been stored for 65 years since its removal from the reactor core.
[5] The axial distances between the wells rely on the assumption that the SNF has been stored for 65 years since its removal from the reactor core.

5.1.2.2 Required safety and technical functions

The conceptual design of the buffer is based on the safety and technical functions that it is required to provide, which can be divided into the following categories:

- Preventing the access of water and aggressive substances to the WDP, retarding of the degradation of the WDP
- Preventing the development of microbiologically influenced corrosion
- Chemical compatibility with the WDP material (no acceleration of the degradation of the WDP)
- Ensuring the removal of heat from the WDP
- Mechanical protection and stabilisation of the position of the WDP
- Minimisation of the transport of, and the retardation of, radionuclides
- Ensuring the removal of generated gases

Prevention of the access of water and aggressive substances to the WDP, retardation of the degradation of the WDP

The buffer material must serve to delay to the greatest extent possible the time at which water reaches the WDP and, subsequently, the SNF; once this occurs, it must then minimise water transport. The presence of groundwater triggers chemical reactions that, *inter alia*, result in the corrosion of the WDP. This function is influenced by the density of the material, its hydraulic properties and its amount (the thickness of the barrier).

Prevention of the development of microbiologically influenced corrosion

The WDP will also be threatened by the activity of the microorganisms that are naturally present in bentonite, and which are able to cause the development of the corrosion of the WDP where it is in contact with the bentonite. Microbial activity can be limited by ensuring the compaction of the bentonite to a high density, the maximisation of the homogeneity of the buffer, the limitation of voids within the buffer (e.g. the technological gaps) and at the interfaces between the buffer and other components and materials (e.g. the rock), and the limitation of the content of organic substances in the bentonite that serve as a source of energy for micro-organisms (see 3.1 for details).

Chemical compatibility with the WDP material (no acceleration of the degradation of the WDP)

The chemical compatibility of the engineered barrier materials serves to extend the time over which the materials do not interact and degrade at the various interfaces. As a result of corrosion, bentonite may degrade at these interfaces, which reduces its retardation properties. At the same time, undesirable spaces for the development of microbial activity may form. Iron will diffuse from the corroded steel into the buffer, which may act to alter the pH and the other geochemical properties of the bentonite. The iron released from the steel will be used by iron-reducing bacteria for their further growth (see the 616/2022 report, Večerník et al., 2022). This function will be influenced by the chemical and mineralogical composition of the buffer, the composition of the groundwater, the microbial composition and its development over time and the conditions in the DGR.

Ensuring the removal of heat from the WDP

The removal of heat from the WDP to the surrounding rock massif is one of the most important functions of the buffer. It must ensure the removal of the heat generated so as to avoid the occurrence of a critical condition caused by the overheating of the WDP with the SNF. Moreover, it is important that the retardation properties of the bentonite are not lost due to the increased temperature. The properties and design of the buffer will exert a direct effect on the temperature of the WDP over time since, from the thermal point of view, the engineered barriers comprise a performance-controlled system, in which the resulting temperature is determined by the balance between the heat source (the heat produced by the WDP and the influence of the surroundings of the WDP) and the efficiency of the removal of the heat. A high level of heat dissipation will require that the buffer is in direct contact with the WDP and the surrounding rock and that the buffer contains no voids (e.g. unfilled technological joints) that could act to provide local thermal insulation. The dissipation of heat is further dependent on the thickness of the buffer (it decreases with increased thickness) and its thermal conductivity (improves with increasing conductivity). The thermal conductivity is dependent on the dry density of the buffer (increases with higher values) and the moisture content (increases with higher values).

Mechanical protection and stabilisation of the position of the WDP

A further function of the buffer is to ensure the position of the WDP and the mechanical protection thereof. The buffer must have sufficient strength and deformable and shear characteristics so that the position of the WDP inside the buffer remains unchanged (e.g. the prevention of the gradual "sinking" of the WDP). Moreover, it must provide mechanical protection for the WDP in case of seismic events. These functions depend on the thickness of the barrier and its mechanical properties, which are influenced by the dry density and the moisture content of the buffer.

The swelling of bentonite affects the closure of voids, joints and the self-healing of discontinuity surfaces. The swelling capacity should be as high as possible. The swelling of bentonite is influenced primarily by the content of smectites, the dry density (i.e. the degree of compaction) and the type of exchangeable cation. As the dry density increases, the swelling pressure increases exponentially. The swelling pressure is higher for bentonites with higher proportions of smectite and bentonites with the predominance of Na+ in the interlayer. The differences in swelling pressures are at low densities and disappear in the range ρ_d ~ 1,500-1,600 kg·m^{-3} (Vašíček et al., 2019).

The presence of colloidal particles leads to the erosion of bentonite, the evaluation of which is possible via the swelling parameter, which may form a part of the material quality control system during the construction of the DGR (Pospíšková et al., 2022).

Minimisation of the transport of, and the retardation of, radionuclides

An equally important function concerns the limitation of the transport of, and the retardation of, radionuclides. Following the penetration of water into the disposed of SNF, water will become the potential radionuclide transport medium. Transport processes (including retardation) depend on the thickness of the buffer (they take longer with greater thicknesses) and its hydraulic properties (permeability, diffusion coefficient, sorption coefficient). These properties are dependent on the dry density of the buffer (increases generally result in decreases in permeability and the other coefficients). The sorption capacity of radionuclides is reflected by the cation exchange capacity (CEC) and the specific surface area (SSA). The cation exchange capacity is one of the most sensitive parameters in terms of reflecting changes in the mineralogical composition and swelling caused by illitisation, cementation and other alteration processes (Dohrmann et al., 2012). The content of reactive Si in bentonite reflects the susceptibility of bentonite to alteration as well as its stability in relation to cement and concrete components.

The chemical composition of the pore water will depend on the properties of the bentonite (its mineralogical composition, the content of clays from the smectite group, the extent of the cation exchange capacity and the occupation of cations at the exchange sites, the content and composition of the non-clay water-soluble minerals), the chemical composition of the groundwater and the physico-chemical parameters of the environment (temperature, pressure, gas phase composition, etc.). The term "pore water" in bentonite is currently referred to by most authors as *"free water"*, which participates in the reactions that take place inside the bentonite (sorption, dissolution, precipitation), and enables the transport of substances by means of diffusion. The volume of pore water in compacted bentonite is then a function of its dry density (Bradbury and Baeyens, 2003).

Ensuring the removal of generated gases

The buffer must also enable the removal of emerging gases (that arise, for example, as a result of the corrosion of the WDP, the radiolysis of water or the gases that are released from the inside of the WDP following damage thereto) and prevent increases in pressure within the engineered barrier system. This function is influenced by the chemical and mineralogical composition of the buffer and its density.

5.1.3 Component design assumptions

The conceptual design is based on:

- the required dimensions as set out in the 580/2022 report (Dohnálková et al., 2022)
- the anticipated interactions as described in the 616/2022 report (Večerník et al., 2022)
- the requirements concerning the safety functions as set out in the 618/2022 report (Pospíšková et. al., 2022)
- technical feasibility
- economic feasibility

A longer spacer block is currently being considered than that set out in the 580/2022 report (Dohnálková et al., 2022) based on the assumed distance between the WDPs. Concerning VVER 440, the length of the spacer block is 3,960 mm, and for VVER 1000, 16,795 mm.

The requirements for the properties of the bentonite are listed in Tab. 6, chapter 3.1

5.1.4 Component description

The disposal boreholes (mine construction entity 09) will be located in the disposal horizon of the DGR. According to the 580/2022 report (Dohnálková et al., 2022), the backfilling of the disposal boreholes will comprise two components: the buffer and the spacer blocks.

- The buffer is one of the engineered barriers made of compacted bentonite; it is emplaced in the disposal borehole and surrounds the WDP.

- The spacer block is also one of the engineered barriers; it is made of compacted bentonite with the same material parameters as the buffer and is emplaced in the disposal borehole so as to ensure the required distance between the individual WDPs.

The use of calcium-magnesium bentonite of Czech origin is assumed.

The conceptual design (Fig. 2) assumes the division of the disposal borehole backfilling into the following subcomponents:

- 01 the bed of the WDP (backfilling beneath the WDP)
- 02 the main backfill (excl. the bed)
- 03 the ground levelling layer
- 04 the backfilling of the technological gaps

The buffer consists of subcomponents 01-04 and the spacer block of subcomponents 02-04.

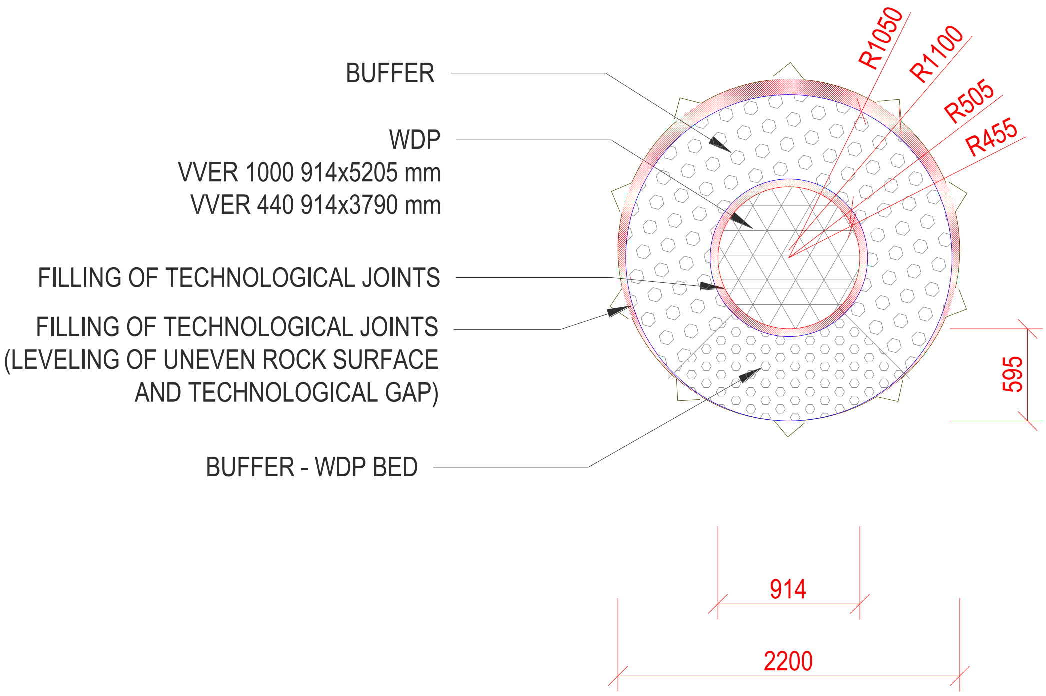

Fig. 2 Cross-section of a disposal borehole with the location of the WDP

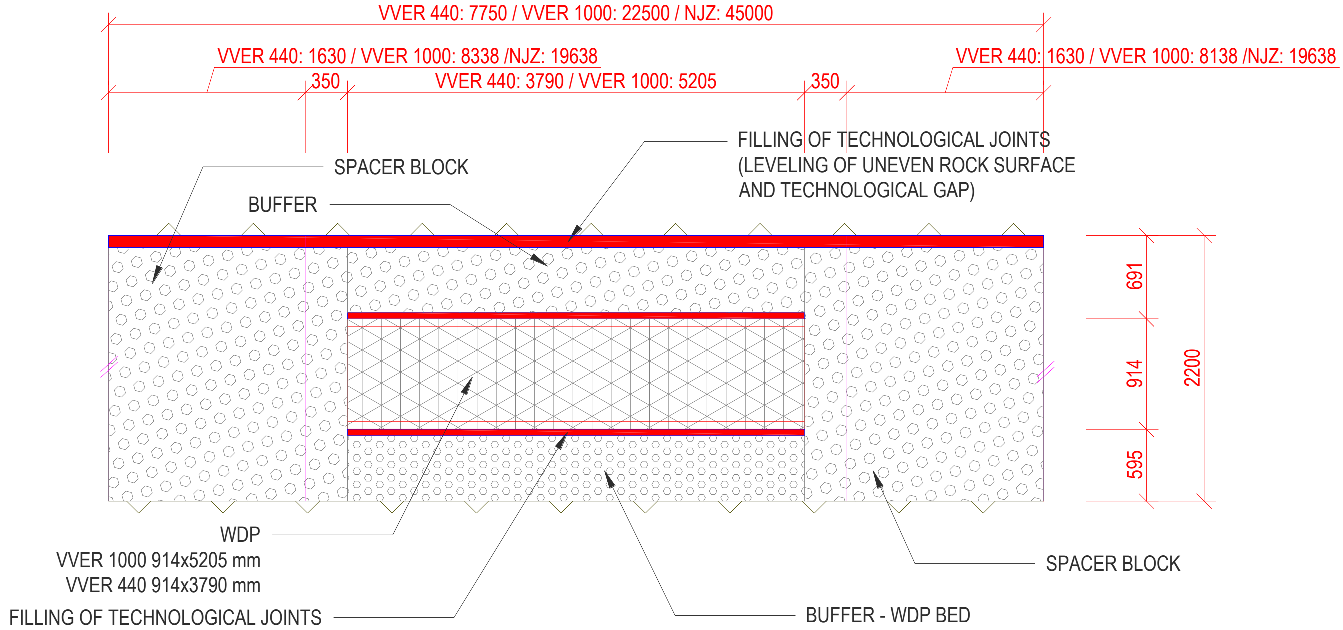

Fig. 3 Vertical longitudinal section through a disposal borehole with a WDP (a single disposal location showing the adjacent part of the spacer block)

Three subvariants of the technical design of the component have been proposed:

- 01 Blocks (entire profile) + gap backfilling (pellets, granulate) (preferred subvariant)
- 02 Blocks (bed) + pelletised material
- 03 Pelletised material throughout the profile

Subvariant 01 assumes the use of compressed blocks as the main material for the buffer and the spacer blocks. Pelletised material will be used to level the ground (if necessary) and for the backfilling of the technological gaps along the WDP and the rock interface.

Subvariant 02 assumes the use of compressed blocks as the main buffer material in the space beneath the WDP (bed). Pelletised material will be used to level the ground (if necessary), to fill the technological gaps along the WDP and the rock interface, for the buffer (excl. the bed) and for the whole of the spacer block.

Subvariant 03 assumes the use of pelletised material throughout the entire buffer profile and for the whole of the spacer block.

5.1.5 Locations of applicability in the DGR

Primary use: disposal borehole with the WDP (mine construction entity 09) – horizontal system.

Secondary use: none

5.1.6 Applicability conditions

- Clean excavation without significant disturbances or active water inflows (the exact criteria will be specified in the future)

- No materials must be introduced into the disposal borehole or loading corridor (e.g. remnants of linings, ground levelling, etc.)

5.1.7 Subvariants and the subcomponents thereof

5.1.7.1 Subvariant 01 Blocks (entire profile) + gap backfilling (pellets, granulate)

This is the **preferred variant** due to the guaranteed attainment of the required dry density of the buffer, i.e. in the area around the WDP 1,653 kg/m^3; more distant from the WDP 1,673 kg/m^3.

Advantages:

- It is guaranteed that the required dry density of the buffer will be achieved
- The maintaining of the position of the WDP in the disposal borehole is guaranteed

Disadvantages:

- Complex preparation process
- Complex installation
- Technological gaps
- Difficult to store and to handle the backfill material

5.1.7.1.1 01 Bed of the WDP (backfilling beneath the WDP)

The bed for the WDP will be made of bentonite blocks of ρ_d = 1,700 kg/m^3. This degree density was chosen so that even in the space around the WDP after the filling of the technological gaps, the required average buffer ρ_d of 1,600 kg/m^3 will be achieved.

The blocks will be pre-assembled into larger units and stored in this form on site. The system for their subsequent division into individual units will be decided following further research, as will the exact dimensions of the bed itself.

The strength of the blocks must be such that the bed does not disintegrate following the emplacement of the WDP.

The geometry of the bed must be such that it allows for the emplacement of the WDP and the backfilling of the remaining space in the disposal borehole.

5.1.7.1.2 02 Main backfill (excl. the bed)

The main backfill will be identical to component 01

5.1.7.1.3 03 Ground levelling layer

The levelling layer in the bottom of the borehole (if required) will be made of pelletised bentonite with a minimum average ρ_d following disposal of 1,400 kg/m^3. The thickness of the levelling layer will depend on the selected disposal borehole excavation technology. The conceptual design assumes a thickness of up to 50 mm.

The properties of component 03 will be identical to those of component 04.

5.1.7.1.4 04 Backfilling of the technological gaps

The technological gaps are a necessary feature from the point of view of borehole tolerances, the handling of the blocks and the potential for the seamless filling of the gaps without the formation of cavities. It is assumed that the size (thickness) of these gaps will be 50 mm.

The exact size of the technological gaps will be specified following the conducting of the optimisation process.

The filling of the technological gaps along the WDP and the borehole walls will consist of pelletised bentonite with a minimum average ρ_d following disposal of 1,400 kg/m^3.

5.1.7.2 Blocks (bed) + pelletised material

Alternative option. Due to technological reasons, it is currently not possible to guarantee the attainment of the required ρ_d of the buffer. This variant theoretically attains[6] an average backfill dry density in the WDP area of 1,613 kg/m^3. The dry density away from the WDP is identical to subvariant 03.

Advantages:

- Easier filling of the main section of the backfill and the whole of the spacer blocks
- Easier storage and handling of the majority of the backfill material
- Fewer technological gaps

Disadvantage:

- Currently, it is not possible to guarantee the attainment of the required dry density of the buffer

5.1.7.2.1 01 Bed of the WDP (filling beneath the WDP)

This subcomponent is identical to the subcomponent in subvariant 01, see chapter 5.1.7.1.1.

5.1.7.2.2 02 Main backfill (excl. the bed)

The main backfilling of the disposal borehole will comprise pelletised material with an average ρ_d following disposal of 1,600 kg/m^3. The backfilling also includes the area of adjacent technological gaps from subvariant 01.

Note: currently, this value cannot be reliably guaranteed. Further technical research is required.

5.1.7.2.3 03 Ground levelling layer

This subcomponent is identical to the design of the subcomponent in subvariant 01, see chapter 5.1.7.1.3.

[6] The value provided in the text assumes the ρ_d of the disposed of pelletised material at 1600 kg/m^3, which is currently not technologically possible.

5.1.7.2.4 04 Filling of the technological gaps (only beneath the WDP)

This subcomponent is identical to subvariant 01 in the area of the bed of the WDP (see chapter 5.1.7.1.4). There is no subcomponent outside the bed of the WDP; the space is included in subcomponent 02.

5.1.7.3 Subvariant 03 Pelletised material throughout the profile

Alternative option. Technologically the most simple approach; however, currently it is not possible to guarantee the attainment of the required ρ_d of the buffer. The variant attains the same average dry density of the backfill.

Advantages:

- Simple installation
- Simpler storage requirements and handling of the material
- No technological gaps

Disadvantages:

- Necessity for the use of a machine to ensure the position of the WDP/preparation of the geometry of the bed.
- Currently, it cannot be guaranteed that the required density of the buffer will be attained

5.1.7.3.1 01 Bed of the WDP (filling beneath the WDP)

The main backfilling of the disposal borehole will comprise pelletised material with an average ρ_d following disposal of 1,600 kg/m^3.

Note: currently, this value cannot be reliably guaranteed. Further technical research is required. Once the technological issues have been solved, it is advisable to switch to this option.

5.1.7.3.2 02 Main backfilling (excl. the bed)

Corresponds to subcomponent 01 (see chapter 5.1.7.3.1).

5.1.7.3.3 03 Ground levelling layer – not required (part of 01)

5.1.7.3.4 04 Filling of the technological gaps – not required (there are no technological gaps)

5.1.8 Production/preparation technology

Industrially mined and processed (homogenised) bentonite will be used for the buffer. The material will be supplied by the manufacturer in pelletised or powder form. The powder (or pelletised form) will be compressed into blocks by the supplier or at the DGR. The prepared material will be stored under suitable conditions until the time of use so that it does not degrade (the disintegration of the blocks) or become contaminated.

Prior to use, the bentonite blocks will be assembled at a suitable location in larger units (whole layer/layers) and prepared for transport to the disposal boreholes and for use by the handling device.

The pelletised form of the material will not need to be modified and will be transported to the disposal site in suitable transport containers.

5.1.9 Installation/construction technology

5.1.9.1 Subvariant 01 Blocks (entire profile) + gap filling (pellets, granulate)

The construction of the disposal borehole backfill will take place as follows:

1) Levelling of the bottom of the disposal borehole with pelletised material (if necessary).
2) Construction of the WDP bed from bentonite blocks
3) Installation of the WDP
4) Installation of the bentonite blocks around and above the WDP. Simultaneous filling of the technological gaps along the WDP and the rock.
5) Installation of the spacer blocks – identical to points 1 and 4, plus the fact that point 4 includes the filling of the blocks along the whole of the profile (no WDP or technological gaps around the WDP).

The following technologies will be used in the construction process:

- Gravity disposal and vibrating plates will be used to level the bottom of the boreholes.
- A vacuum handling device will be used to install the main part of the buffer; the device will be able to emplace multiple blocks at once.
- The handling device will be used for the installation and temporary stabilisation of the WDPs.
- Mechanical (conveyor) and/or pneumatic transport methods with vibration compaction (immersion rods) will be used to fill the technological gaps. The size of the technological gaps will be chosen with regard to the selected backfilling technology so that there are no voids. Moreover, it will be necessary to ensure the sufficient level of density of the backfilling.

Note: The technology for the filling of the joints will have to be integrated into the construction technology of the main part of the buffer (block handling device). When backfilling, it will be necessary to gradually “retreat” in short sections in which the backfilling of the section with blocks will be followed by the filling of the technological gaps. It is possible that the section will have to be temporarily supported/reinforced.

5.1.9.2 Subvariant 02 Blocks (the bed) + pelletised material

The construction of the disposal borehole backfill will take place as follows:

1) Levelling of the bottom of the disposal borehole with pelletised material (if necessary)
2) Construction of the WDP bed from bentonite blocks
3) Installation of the WDP
4) Installation of the pelletised material around and above the WDP
5) Installation of the spacer blocks – identical to point 4, plus the fact that point 4 includes backfilling with pelletised material along the whole of the profile (no WDP or technological gaps around the WDP).

The following technologies will be used in the construction process:

- Gravity disposal and vibrating plates will be used to level the bottom of the boreholes
- A vacuum handling device will be used to install the main part of the buffer; the device will be able to emplace multiple blocks at once
- The handling device will be used for the installation and temporary stabilisation of the WDPs
- Mechanical (conveyor) and/or pneumatic transport methods with vibration compaction (immersion rods) will be used for backfilling with the exception of the WDP bed and the technological gaps. It will be necessary to ensure the sufficient level of density of the backfilling. It will also be necessary to gradually "retreat" during the backfilling procedure. It is likely that the backfilling will need to be temporarily supported/reinforced.

5.1.9.3 Subvariant 03 Pelletised material throughout the whole of the profile

The construction of the disposal borehole backfill will take place as follows:

1) Backfilling of the lower half of the disposal borehole, leaving space for the WDP.
2) Compaction/creation of a precise space for the WDP (equivalent to the bed) using a vibration plate of the appropriate form.
3) Installation of the WDP
4) Installation of the pelletised material around and above the WDP
5) Installation of the spacer blocks – identical to point 4, plus the fact that point 4 includes backfilling with pelletised material along the whole of the profile (no WDP or technological gaps around the WDP).

The following technologies will be used in the construction process:

- The handling device will be used for the installation and temporary stabilisation of the WDP
- Mechanical (conveyor) and/or pneumatic transport methods with vibration compaction (immersion rods) will be used for backfilling purposes. It will be necessary to ensure the sufficient level of density of the backfilling. It will also be necessary to gradually "retreat" during the backfilling procedure. It is likely that the backfilling will need to be temporarily supported/reinforced
- A vibration plate of the appropriate form will be used for the preparation of the bed of the WDP.

5.1.10 Estimation of unit prices

The estimation of the prices of bentonite-based backfilling is based on the prices stated in the 134/2017 report (Grünwald et al., 2018) and increased in line with the inflation rate in the period 2018-2022. The price determination procedure is described in chapter 4.2. Tab. 14 shows the cubic capacity of the material used to calculate the prices, which are shown in Tab. 15. The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 14 Amounts of material required for the various VY01.01 options

			VVER 440	VVER 1000	NNS
		Bentonite ρ_d [kg/m^3]	Amount of material [m^3]	Amount of material [m^3]	Amount of material [m^3]
01 Blocks (entire profile) + gap filling (pellets, granulate) (preferred subvariant)	01 Bed of the WDP (backfill beneath the WDP)	1,700	23.2	72.8	153.3
	02 Main backfill (excl. the bed)				
	03 Ground levelling layer	1,400	3.2	8.5	16.5
	04 Filling of the technological gaps				
02 Blocks (bed) + pelletised material	01 Bed of the WDP (backfill beneath the WDP)	1,700	2.7	3.6	3.6
	02 Main backfill (excl. the bed)	1,600	22.8	75.8	163.2
	03 Ground levelling layer	1,400	0.5	0.7	0.7
	04 Filling of the technological gaps				
03 Pelletised material throughout the profile	Bed of the WDP (backfill beneath the WDP)	1,600	26.0	80.0	167.2
	02 Main backfill (excl. the bed)				
	03 Ground levelling layer				
	04 Filling of the technological gaps				

Tab. 15 Estimated prices of the VY 01.01 components

	Total price of the subvariant for one disposal location		
	VVER 440	VVER 1000	NNS
	CZK thousand	CZK thousand	CZK thousand
01 Blocks (entire profile) + gap filling (pellets, granulate) (preferred subvariant)	356	1,099	2,299
02 Blocks (bed) + pelletised material	338	1,040	2,173
03 Pelletised material throughout the profile	337	1,037	2,167

5.2 VY 01.02 Disposal borehole backfill – horizontal disposal borehole with a diameter of 1.7 m

5.2.1 Component details

Name	Disposal borehole backfilling (buffer) - horizontal disposal borehole
Description	Backfilling of the disposal borehole - horizontal WDP disposal method
Location in the DGR	Disposal borehole
Applicability conditions	• Clean excavation without significant disturbances or active water inflows (the exact criteria will be specified in the future) • No materials must be introduced into the disposal borehole or loading corridor (e.g. lining remnants, ground levelling, etc.)
Subvariants	01 Blocks (entire profile) + gap filling (pellets, granulate) (preferred subvariant) 02 Blocks (bed) + pelletised material 03 Pelletised material throughout the whole of the profile
Material	Bentonite
Subcomponents	01 Bed of the WDP (backfilling beneath the WDP) 02 Main backfill (excl. the bed) and in the spacer block 03 Ground levelling layer 04 Filling of the technological gaps Note: Borehole closure, see VY 06.01 Horizontal disposal borehole operational plug
Production/preparation technology	Industrially processed bentonite in the form of pelletised material and blocks.
Installation/construction technology	01 Assemblage from prefabricated components (compressed parts) 02 Backfilling pneumatically or using a mechanical conveyor (screw conveyor, gravity transport, vibrating conveyor), on-site compaction

5.2.2 Component requirements

Identical to VY 01.01; see chapter 5.1.2. Only the diameter of the borehole has been adjusted to the minimum while maintaining the requirements concerning the thickness of the barrier and its dry density.

5.2.3 Component design assumptions

Identical to VY 01.01; see chapter 5.1.3. The component differs only in terms of the diameter of the disposal tunnel. The diameter was kept to the minimum while maintaining a thickness of the bentonite backfilling of at least 350 mm.

5.2.4 Component description

Identical to VY 01.01; see chapter 5.1.4 and Fig. 4. The component comprises an alternative solution for a smaller disposal borehole diameter; only the dimensions of the borehole differ. There are no plans for a technological joint around the WDP.

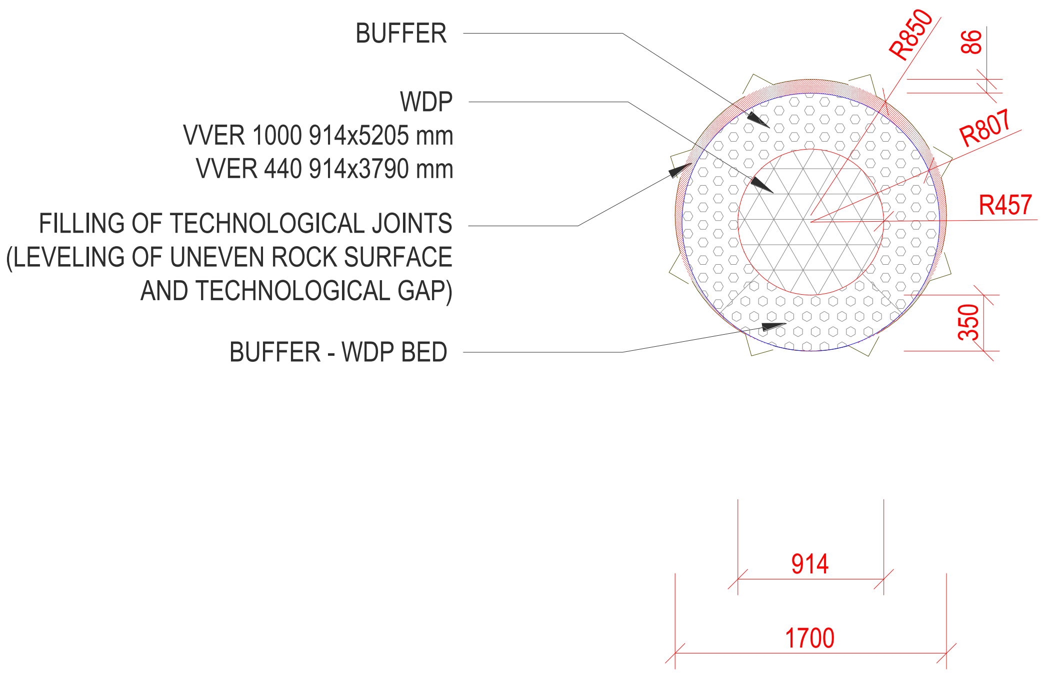

Fig. 4 Cross-section of the disposal borehole at the location of the WDP

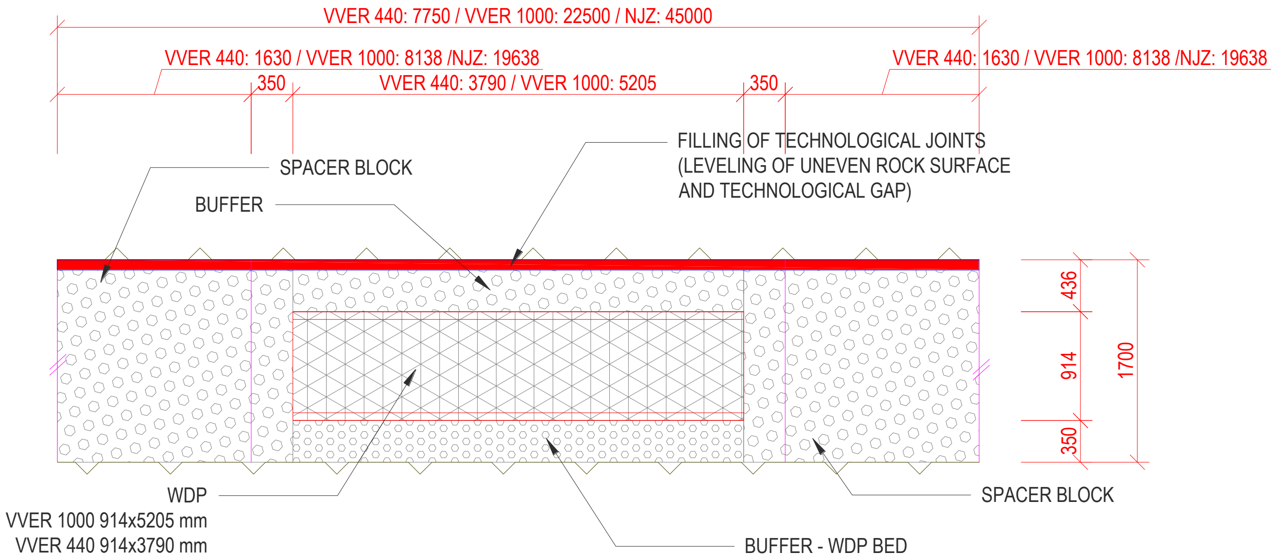

Fig. 5 Vertical longitudinal section through the disposal borehole at the location of the WDP (one disposal place, and showing the adjacent part of the spacer block)

5.2.5 Locations of applicability in the DGR

Primary use: Disposal borehole with the WDP (DuSO 09) – horizontal system.

Secondary use: None

5.2.6 Conditions of use

Identical to VY 01.01; see chapter 5.1.6.

5.2.7 Subvariants and their subcomponents

5.2.7.1 Subvariant 01 Blocks (entire profile) + gap filling (pellets, granulate)

This is the **preferred variant** due to the guaranteed attainment of the required density of the buffer. This variant has an average backfill dry density of: in the area around the WDP 1,658 kg/m^3; more distant from the WDP 1,670 kg/m^3.

Advantages:

- It is guaranteed that the required density of the buffer will be attained
- The position of the WDP in the disposal borehole is guaranteed

Disadvantages:

- Complex preparation procedure
- Complex installation procedure
- Technological gaps
- Difficult to store and to handle the backfilling material

5.2.7.1.1 01 Bed of the WDP (backfill beneath the WDP)

The bed of the WDP will be made of bentonite blocks ρ_d = 1,700 kg/m^3. The density was chosen so that even in the space around the WDP after the filling of the technological gaps, the required average buffer ρ_d of 1,600 kg/m^3 will be attained.

The blocks will be pre-assembled into larger units and stored in this form. The system for their subsequent division into individual units will be decided following further research, as will the exact dimensions of the bed itself.

The strength of the blocks must be such that the bed does not disintegrate following the emplacement of the WDP.

The geometry of the bed must be such that it allows for the emplacement of the WDP and the backfilling of the remaining space in the disposal borehole.

5.2.7.1.2 02 Main backfill (excl. the bed)

The main backfill will be identical to subcomponent 01.

5.2.7.1.3 03 Ground levelling layer - none

5.2.7.1.4 04 Filling of the technological gaps

The technological gaps are a necessary feature from the point of view of borehole tolerances, the handling of the blocks and the potential for the seamless filling of the gaps without the formation of cavities. It is assumed that the size (thickness) of these gaps will be 0-86 mm.

The exact size of the technological gaps will be specified following the conducting of the optimisation process.

The filling of the technological gaps along the WDP and the borehole walls will consist of pelletised bentonite with a minimum average ρ_d following disposal of 1,400 kg/m^3.

5.2.7.2 Subvariant 02 Blocks (bed) + pelletised material

Alternative option. Due to technological reasons, it is currently not possible to guarantee the attainment of the required ρ_d of the buffer. This variant theoretically attains[7] an average backfill dry density in the WDP area of 1,614 kg/m^3. The dry density away from the WDP is identical to subvariant 03.

Advantages

- Easier filling of the main section of the backfill and the whole of the spacer blocks
- Easier storage and handling of the majority of the backfill material
- Fewer technological gaps

Disadvantage:

[7] The value provided in the text assumes the ρ_d of the disposed of pelletised material at 1600 kg/m^3, which is currently not technologically possible.

- Currently, it is not possible to guarantee the attainment of the required dry density of the buffer

5.2.7.2.1 01 Bed of the WDP (backfill beneath the WDP)

This subcomponent is identical to subvariant 01.

5.2.7.2.2 02 Main backfilling (excl. the bed)

The main backfilling of the disposal borehole will comprise pelletised material with an average ρ_d following disposal of 1,600 kg/m^3. The backfilling also includes the area of adjacent technological gaps from subvariant 01.

Note: currently, this value cannot be reliably guaranteed. Further technical research is required.

5.2.7.2.3 03 Ground levelling layer

This subcomponent is identical to subvariant 01.

5.2.7.2.4 04 Backfilling of the technological gaps

This subcomponent is identical to subvariant 01 in the area of the WDP bed. There is no subcomponent away from the WDP; the space is included in subcomponent 02.

5.2.7.3 Subvariant 03 Pelletised material throughout the profile

Alternative option. Technologically the most simple approach; however, currently it is not possible to guarantee the attainment of the required ρ_d of the buffer. The variant attains the same average dry density of the backfill.

Advantages:

- Simple installation
- Simpler storage requirements and handling of the material
- No technological gaps

Disadvantages:

- More complex positioning of the WDP/preparation of the geometry of the bed.
- Currently, it cannot be guaranteed that the required density of the buffer will be attained

5.2.7.3.1 01 Bed of the WDP (backfilling beneath the WDP)

The main backfilling of the disposal borehole will comprise pelletised material with an average ρ_d following disposal of 1,600 kg/m^3.

Note: currently, this value cannot be reliably guaranteed. Further technical research is required. Once the technological issues have been solved, it is advisable to switch to this option.

5.2.7.3.2 02 Main backfilling (excl. the bed)

Identical to subcomponent 01.

5.2.7.3.3 03 Ground levelling layer – not required (it is part of 01)

5.2.7.3.4 04 Filling of the technological gaps – not required (there will be no technological gaps)

5.2.8 Production/preparation technology

Industrially mined and processed (homogenised) bentonite will be used for the buffer. The material will be supplied by the manufacturer in pelletised or powder form. The powder (or pelletised form) will be compressed into blocks by the supplier or at the DGR. The prepared material will be stored under suitable conditions until the time of use so that it does not degrade (the disintegration of the blocks) or become contaminated.

Prior to use, the bentonite blocks will be assembled at a suitable location in larger units (whole layer/layers/disposal place) and prepared for transport to the disposal boreholes and for use by the handling device.

The pelletised form of the material will not need to be modified and will be transported to the disposal site in suitable transport containers.

5.2.9 Installation/construction technology

5.2.9.1 Subvariant 01 Blocks (whole of the profile) + gap filling (pellets, granulate)

The construction of the disposal borehole backfill will take place as follows:

1) Assemblage of the bed inside the handling device (outside the borehole)
2) Installation of the WDP inside the handling device (outside the borehole)
3) Assemblage of the main backfilling inside the handling device (outside the borehole)
4) Installation of the WDP assembly with the handling device backfilling. Simultaneous filling of the technological gaps along the rock.
5) Installation of the spacer blocks – identical to points 1 and 4, plus the fact that point 4 includes the filling of the blocks along the whole of the profile (no WDP or technological gaps around the WDP).

The following technologies will be used in the construction process:

- Gravity disposal and vibrating plates will be used to level the bottom of the wells.
- A vacuum handling device will be used to install the main part of the buffer; the device will be able to emplace multiple blocks at once.
- The handling device will be used for the installation and temporary stabilisation of the WDPs.
- Mechanical (conveyor) and/or pneumatic transport methods with vibration compaction (immersion rods) will be used to fill the technological gaps. The size of the technological gaps will be chosen with regard to the selected backfilling technology so that there are no voids. Moreover, it will be necessary to ensure the sufficient level of density of the backfilling.

Note: The technology for the filling of the joints will have to be integrated into the construction technology of the main part of the buffer (block handling device). When backfilling, it will be necessary to gradually “retreat” in short sections in which the backfilling of the section with blocks will be followed by the filling of the technological gaps. It is possible that the section will have to be temporarily supported/reinforced.

5.2.9.2 Subvariant 02 Blocks (the bed) + pelletised material

The construction of the disposal borehole backfill will take place as follows:

1) Levelling of the bottom of the disposal borehole with pelletised material (if necessary).
2) Construction of the bed of the WDP from bentonite blocks
3) Installation of the WDP
4) Installation of pelletised material around and above the WDP.
5) Installation of the spacer blocks – identical to point 4, plus the fact that point 4 includes backfilling with pelletised material along the whole of the profile (no WDP or technological gaps around the WDP).

The following technologies will be used in the construction process:

- Gravity disposal and vibrating plates will be used to level the bottom of the wells.
- A vacuum handling device will be used to install the main part of the buffer; the device will be able to emplace multiple blocks at once.
- The handling device will be used for the installation and temporary stabilisation of the WDPs.
- Mechanical (conveyor) and/or pneumatic transport methods with vibration compaction (immersion rods) will be used to backfill the areas away from the WDP bed and the technological gaps. The sufficient density of the backfilling will have to be ensured. It will also be necessary to gradually “retreat” during the backfilling procedure. It is likely that the backfilling will need to be temporarily supported/reinforced

5.2.9.3 Subvariant 03 Pelletised material throughout the profile

The construction of the disposal borehole backfill will take place as follows:

1) Backfilling of the lower half of the disposal borehole, leaving space for the WDP.
2) Compaction/creation of a precise space for the WDP (equivalent to the bed) using a vibration plate of the appropriate form.
3) Installation of the WDP
4) Installation of pelletised material around and above the WDP.
5) Installation of the spacer blocks – identical to point 4, plus the fact that point 4 includes backfilling with pelletised material along the whole of the profile (no WDP or technological gaps around the WDP).

The following technologies will be used in the construction process:

- The handling device will be used for the installation and temporary stabilisation of the WDPs.
- Mechanical (conveyor) and/or pneumatic transport methods with vibration compaction (immersion rods) will be used to install the backfill. The sufficient density of the backfilling will have to be ensured. It will also be necessary to gradually “retreat” during the backfilling procedure. It is likely that the backfilling will need to be temporarily supported/reinforced

- A vibration plate of the appropriate form will be used to prepare the bed of the WDP

5.2.10 Estimation of unit prices

The estimation of the prices of bentonite-based backfilling is based on the prices stated in the 134/2017 report (Grünwald et al., 2018) and increased in line with the inflation rate in the period 2018-2022. The price determination procedure is described in chapter 4.2. Tab. 16 shows the cubic capacity of the material used to calculate the prices, which are shown in Tab. 17. The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 16 Amounts of material required for the various VY01.02 options

			VVER 440	VVER 1000	NNS
		Bentonite ρ_d [kg/m^3]	Amount of material [m^3]	Amount of material [m^3]	Amount of material [m^3]
01 Blocks (entire profile) + gap filling (pellets, granulate) (preferred subvariant)	01 Bed of the WDP (backfill beneath the WDP)	1,700	13.1	42.5	90.8
	02 Main backfill (excl. the bed)				
	03 Ground levelling layer	1,400	1.7	5.1	10.4
	04 Filling of the technological gaps				
02 Blocks (bed) + pelletised material	01 Bed of the WDP (backfill beneath the WDP)	1,700	1.5	2.1	2.1
	02 Main backfill (excl. the bed)	1,600	13.2	45.0	97.9
	03 Ground levelling layer	1,400	0.4	0.5	0.5
	04 Filling of the technological gaps				
03 Pelletised material throughout the profile	01 Bed of the WDP (backfill beneath the WDP)	1,600	14.5	46.5	98.7
	02 Main backfill (excl. the bed)				
	03 Ground levelling layer				
	04 Filling of the technological gaps				

Tab. 17 Estimated prices of the VY 01.02 components

	Total price of the subvariant for one disposal location		
	VVER 440	VVER 1000	NNS
	CZK thousand	CZK thousand	CZK thousand
01 Blocks (entire profile) + gap filling (pellets, granulate) (preferred subvariant)	199	643	1,368
02 Blocks (bed) + pelletised material	196	618	1,303
03 Pelletised material throughout the profile	188	603	1,280

5.3 VY 01.03 Disposal borehole backfill (buffer) – vertical disposal borehole

5.3.1 Component details

Name	Disposal borehole backfilling (buffer) - vertical disposal borehole
Description	Backfilling of the disposal borehole - vertical WDP disposal method
Location in the DGR	Disposal borehole in a disposal corridor
Applicability conditions	• Clean excavation without significant disturbances or active water inflows (the exact criteria will be specified in the future) • No materials must be introduced into the disposal borehole or loading corridor (e.g. lining remnants, ground levelling, etc.)
Subvariants	01 Blocks + pelletised material (preferred subvariant) 02 Pelletised material
Material	Bentonite
Subcomponents	01 Main backfill 02 Spacer blocks 03 Ground levelling layer 04 Filling of the technological gaps
Production/preparation technology	Industrially processed bentonite in the form of pelletised material and blocks.
Installation/construction technology	01 Assemblage from prefabricated components (compressed parts) + filling of the technological gaps using technology 02 02 Backfilling pneumatically or using a mechanical conveyor (screw conveyor, gravity transport, vibrating conveyor), on-site compaction

5.3.2 Component requirements

5.3.2.1 External requirements and specifications

5.3.2.1.1 Requirements from the 580/2022 report

The 580/2022 technical report (Dohnálková et al., 2022) sets out the following requirements for the backfilling of the disposal borehole and the related components.

Backfill (buffer and spacer block):

- ρ_d (of the whole of the barrier): 1,600 kg/m^3
- Moisture content after the emplacement of the buffer: at least such that it sufficiently removes the heat from the WDP, the surface temperature of which must not be in excess of 95°C (this condition is set so as to avoid the alteration of the bentonite)

Buffer:

- Width: 368 mm
- Thickness below the WDP: 350 mm
- Thickness above the WDP: 350 mm

Spacer block:

- Width *(diameter)*: 1,650 mm
- Length[8] *(height)*: 500 mm

Borehole:

- Diameter of the disposal borehole: 1,650 mm (for all types of SNF)
- The depth of the disposal borehole depends on the type of SNF (Grünwald et al., 2018)
  - VVER 440: 4,940 mm
  - VVER 1000: 6,575 mm
  - NNS: 6,575 mm
- Axial distance between the individual boreholes (Grünwald et al., 2018)
  - VVER 440: 4,600 mm
  - VVER 1000: 7,750 mm
  - NNS: 18,000 mm
- The zone affected by excavation around the disposal borehole is 350 mm (Grünwald et al., 2018).

WDP:

- Maximum temperature on the surface of the WDP: 95°C
- Specifications of the WDP according to the SNF:
  - VVER 440: h = 3,970 mm, d = 914 mm
  - VVER 1000: h = 5,205 mm, d = 914 mm
  - NNS: not yet determined
- Proposed ambient pressure on the WDP: up to 20 MPa

[8] This length (height) will probably be insufficient; it will have to be verified in the future. The concept also proposes a minimum spacer block height of 2 m.

5.3.2.2 Required safety and technical functions

The conceptual design of the buffer is based on the safety and technical functions that it will be required to provide. They can be divided into the following categories:

- Minimisation of the access of water and aggressive materials to the WDP, retardation of the degradation of the WDP
- Prevention/minimisation of the development of microbiologically influenced corrosion
- Chemical compatibility with the WDP materials (no acceleration of the degradation of the WDP)
- Ensuring the removal of heat from the WDP
- Mechanical protection and stabilisation of the position of the WDP
- Minimisation of the transport, and the retardation, of radionuclides
- Provide for/enable the evacuation of generated gases

For more information, see chapter 5.1.2 – the required safety functions are the same as the VY 01.01 component, but with a slightly different function for the spacer block. According to the vertical concept, one of the most important functions of the spacer block is to ensure the spatial stability of the buffer against displacement (swelling) towards the backfill.

5.3.3 Component design assumptions

The conceptual design is based on:

- the required dimensions as specified in the 580/2022 report (Dohnálková et al., 2022)
- the expected interactions as described in the 616/2022 report (Večerník et al., 2022)
- the requirements for the safety functions set out in the 618/2022 report (Pospíšková et. al., 2022)
- technical feasibility
- economic feasibility

Compared to the requirements of the 580/2022 report (Dohnálková et al., 2022), a higher spacer block is currently being considered. According to preliminary calculations, the proposed height of 500 mm will be insufficient and will not ensure the spatial stability of the buffer against displacement (swelling) towards the backfill. The Swedish and Finnish concepts assume a significantly higher spacer block. Hence, a spacer block with a height of 2,000 mm is in the design phase. This height must be further verified via the creation of a calculation/mathematical model. The total depth of the disposal borehole will have to be increased accordingly.

The requirements for the properties of the bentonite are listed in Tab. 6 in chapter 3.1

5.3.4 Component description

The disposal borehole (DuSO 09) is located in the loading corridor (DuSO 08) in the disposal horizon of the DGR. According to the 580/2022 report (Dohnálková et al., 2022), the backfilling of the disposal borehole will consist of two parts: the buffer and the spacer block.

- The buffer is one of the engineered barriers made of compacted bentonite; it is emplaced in the disposal borehole and surrounds the WDP.

- The spacer block is an engineered barrier that is made of compacted bentonite with the same material parameters as the buffer and is emplaced in the mouth of the disposal borehole above the WDP and the buffer. The spacer block provides a buffer against excessive swelling in the direction towards the mouth of the borehole.

The use of calcium-magnesium bentonite of Czech origin is assumed.

The conceptual design (Fig. 5 and Fig. 7) assumes the division of the disposal borehole backfilling into the following subcomponents:

- 01 the main backfill
- 02 the spacer block
- 03 the ground levelling layer
- 04 the backfilling of the technological gaps

The buffer consists of subcomponents 01, 03 and 04. The spacer block is technically identical to the buffer (from the area away from the WDP).

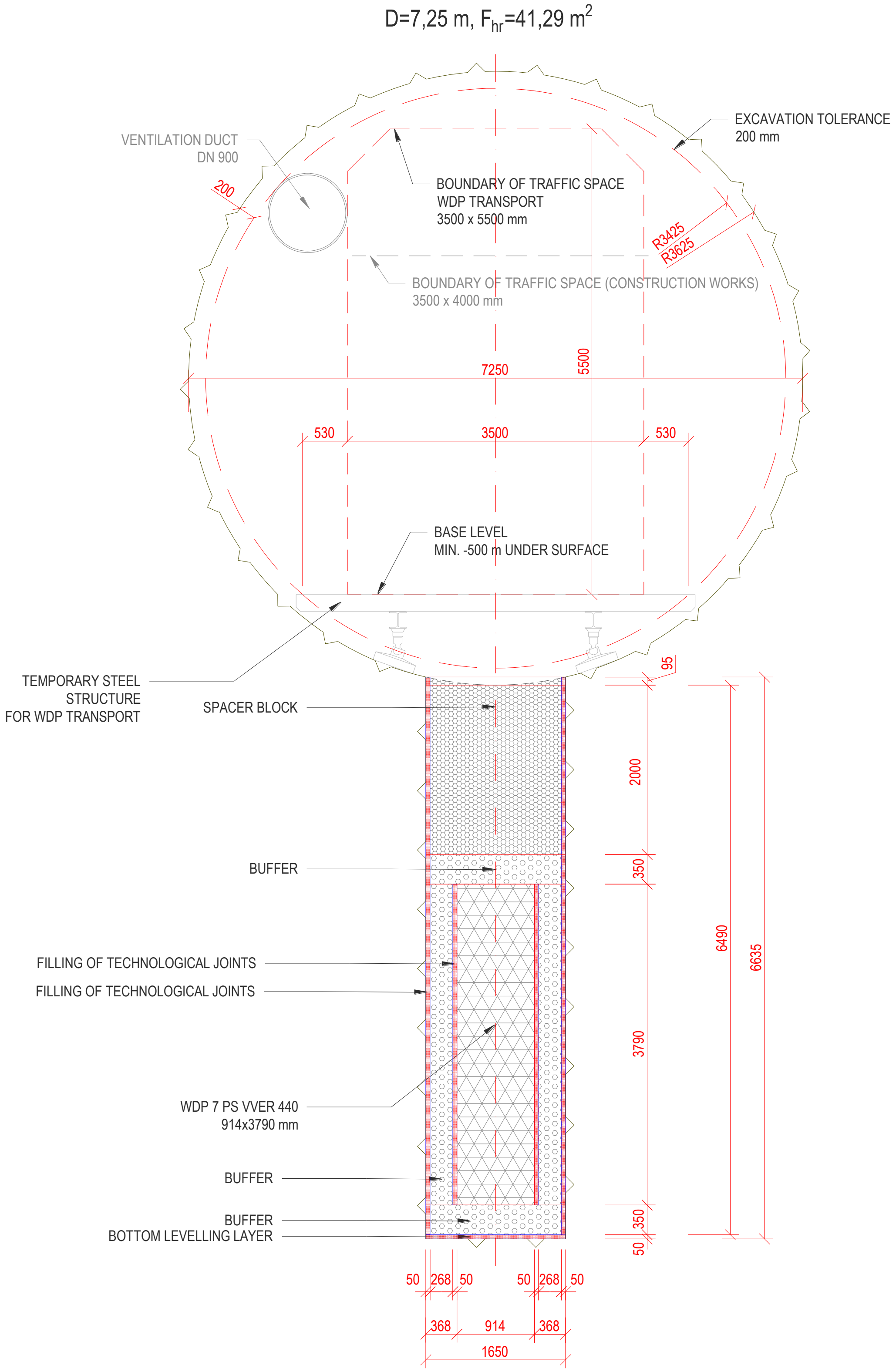

Fig. 6 Cross-section of a disposal borehole – vertical system (VVER 440 version)

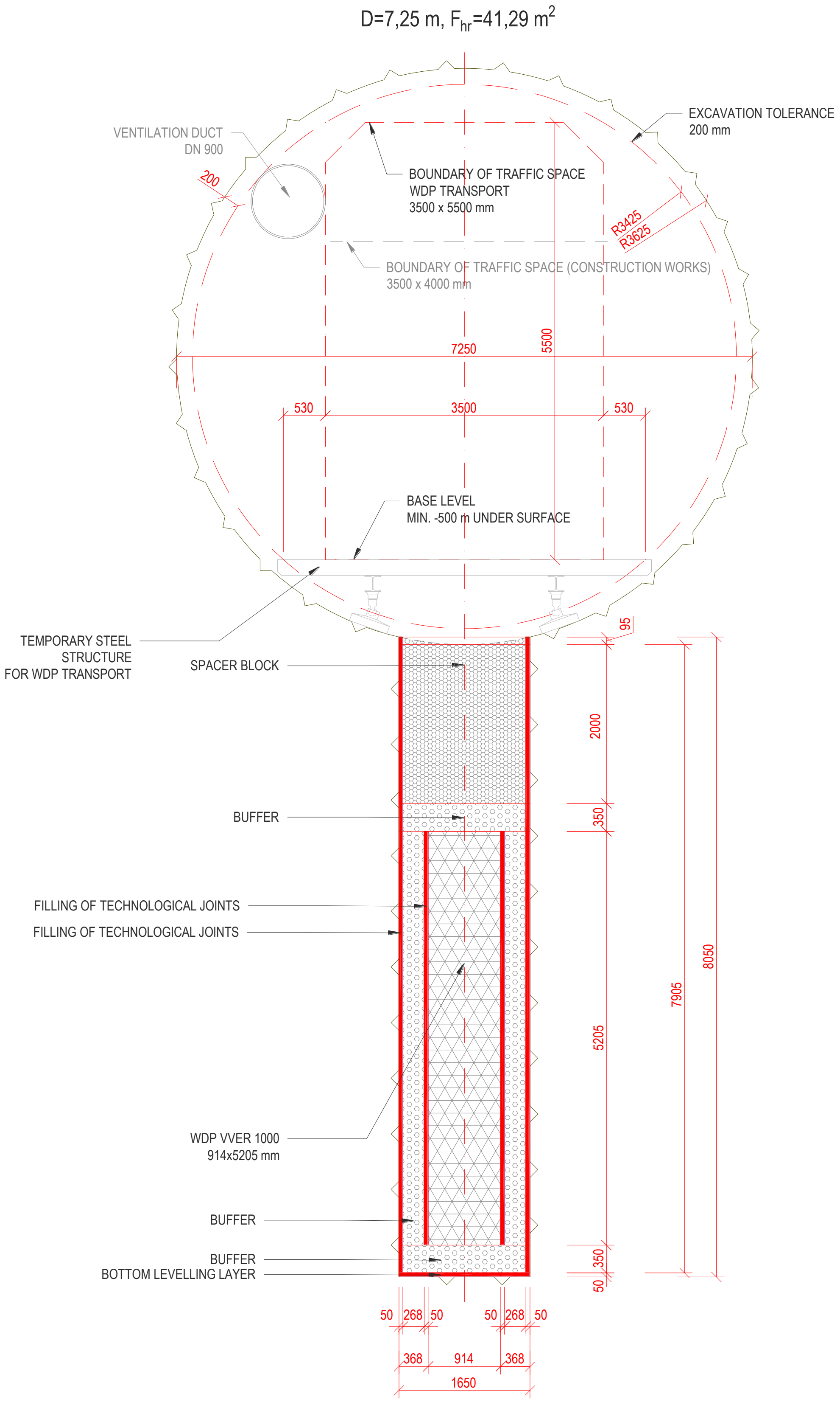

Fig. 7 Cross-section of a disposal borehole – vertical system (VVER 1000 version)

Two subvariants of the technical design of the component have been proposed:

- 01 Blocks + pelletised material (preferred)
- 02 Pelletised material

Subvariant 01 assumes the use of compressed blocks as the main material for the backfilling of the buffer and the spacer blocks. Pelletised material will be used to level the bottom of the borehole (if necessary) and for the backfilling of the technological gaps along the WDP and the rock interface.

Subvariant 02 assumes the use of pelletised material for the whole of the buffer and the spacer block. There will be no need to level the bottom of the borehole or to fill the technological gaps (they will not occur).

5.3.5 Locations of applicability in the DGR

Primary use: backfilling of the vertical disposal borehole with the WDP from the disposal corridor - vertical system. Mine construction entity DuSO 09.

Secondary use: none

5.3.6 Applicability conditions

Identical to VY 01.01. See chapter 5.1.6.

5.3.7 Subvariants and the subcomponents thereof

5.3.7.1 Subvariant 01 Blocks + pelletised material

This is the **preferred variant** due to the guaranteed attainment of the required dry density of the buffer. The variant achieves an average dry density of the backfilling: in the area below and above the WDP 1,664 kg/m^3; around the WDP 1,618 kg/m^3.

Advantages:

- It is guaranteed that the required dry density of the buffer will be achieved
- The maintaining of the position of the WDP in the disposal borehole is guaranteed

Disadvantages:

- Complex preparation process
- Complex installation
- Technological gaps
- Difficult to store and to handle the backfill material

5.3.7.1.1 01 Main backfill

The main backfilling of the disposal borehole will consist of bentonite blocks ρ_d = 1,700 kg/m^3. This density was chosen so that even in the space around the WDP, after the filling of the technological gaps, the required average buffer ρ_d of 1,600 kg/m^3 will be achieved.

The blocks will be pre-assembled in layers and stored layer-by-layer. The system for their subsequent division into individual units and the height of the layers will be decided following further research.

5.3.7.1.2 02 Spacer block

The spacer block will be technically identical to subcomponent 01 (the main backfill), but will be located in the area away from the WDP.

03 Bottom levelling layer

The levelling layer in the bottom of the borehole will be made of pelletised bentonite with a minimum average ρ_d following disposal of 1,400 kg/m^3. The thickness of the levelling layer will depend on the selected disposal borehole excavation technology. The conceptual design assumes a thickness of 50 mm.

The properties of component 03 will be identical to those of component 04.

04 Backfilling of the technological gaps

The technological gaps are a necessary feature from the point of view of borehole tolerances and the handling of the WDP. The potential for the seamless filling of the gaps without the formation of cavities is essential. It is assumed that the size (thickness) of these gaps will be 50 mm.

The exact size of the technological gaps will be specified following the conducting of the optimisation process.

The filling of the technological gaps along the WDP and the borehole walls will consist of pelletised bentonite with a minimum average ρ_d following disposal of 1,400 kg/m^3.

5.3.7.2 Subvariant 02 Pelletised material

Alternative option. Technologically the most simple approach; however, currently it is not possible to technically guarantee the attainment of the required ρ_d of the buffer.

Advantages:

- Simple installation
- Simpler storage requirements and handling of the backfill material
- No technological gaps

Disadvantages:

- Currently, it cannot be guaranteed that the required density of the buffer will be attained

5.3.7.2.1 01 Main backfill

The main backfilling of the disposal borehole will comprise pelletised material with an average ρ_d following disposal of 1,600 kg/m^3.

Note: currently, this value cannot be reliably guaranteed. Further technical research is required.

5.3.7.2.2 02 Spacer block

The spacer block will be technically identical to subcomponent 01 (the main backfill in the area away from the WDP).

5.3.7.2.3 03 Ground levelling layer – not required (part of 01)

5.3.7.2.4 04 Filling of the technological gaps – not required (there are no technological gaps)

5.3.8 Production/preparation technology

Identical to component 01.01. See chapter 5.1.8.

5.3.9 Installation/construction technology

5.3.9.1 Subvariant 01 Blocks + pelletised material

The construction of the disposal borehole backfill will take place as follows:

1) Levelling of the bottom of the disposal borehole with pelletised material (if necessary)
2) Construction of the main part of the buffer from blocks up to the upper level of the WDP
3) Installation of the WDP
4) Filling of the technological gaps along the WDP and the rock
5) Installation of the remaining main part of the buffer and the spacer block
6) Filling of the technological gap along the rock

Note: Depending on the mechanisation employed, the filling of the technological gap along the rock may be performed simultaneously with the construction of the main part of the buffer and the spacer block.

The following technologies will be used in the construction process:

- Gravity disposal and vibrating plates will be used to level the bottom of the wells.
- A vacuum handling device will be used to install the main part of the buffer; the device will be able to emplace multiple blocks at once.
- The handling device will be used for the installation and temporary stabilisation of the WDPs.
- Gravity and/or pneumatic transport methods with vibration compaction (immersion rods) will be used to fill the technological gaps. The size of the technological gaps must be chosen with regard to the selected backfilling technology so that there are no voids. Moreover, it will be necessary to ensure the sufficient level of density of the backfilling.

Note: It is advisable that the technology for the filling of the gaps be integrated with the construction technology of the main part of the buffer (the block handling device).

5.3.9.2 Subvariant 02 Pelletised material

The construction of the disposal borehole backfill will take place as follows:

1) Backfilling of the disposal borehole below the level of the WDP
2) Installation of the WDP and its temporary stabilisation.

3) Backfilling of the space around the WDP.
4) Removal of the WDP stabilisation
5) Backfilling of the space above the WDP up to the mouth of the borehole (buffer + spacer block).

The following technologies will be used in the construction process:

- Gravity and/or pneumatic or mechanical transport methods with vibration compaction (immersion rods, vibrating plates) will be used for the emplacement of the backfilling.
- The handling device will be used for the installation of the WDP, which will also serve for the temporary stabilisation of the WDP during the backfilling of the space around the WDP.

5.3.10 Estimation of unit prices

The estimation of the prices of bentonite-based backfilling is based on the prices stated in the 134/2017 report (Grünwald et al., 2018) and increased in line with the inflation rate in the period 2018-2022. The price determination procedure is described in chapter 4.2. Tab. 18 shows the cubic capacity of the material used to calculate the prices, which are shown in Tab. 19. The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 18 Amounts of material required for the various VY01.03 options

			VVER 440	VVER 1000	NNS
		Bentonite ρ_d [kg/m^3]	Amount of material [m^3]	Amount of material [m^3]	Amount of material [m^3]
01 Blocks + pelletised material (preferred subvariant)	01 Main backfill	1,700	5.5	7.1	7.1
	02 Spacer block	1,700	3.8	3.8	3.8
	03 Ground levelling layer	1,400	0.1	0.1	0.1
	04 Filling of the technological gaps	1,400	2.0	2.6	2.6
02 Pelletised material	01 Main backfill	1,600	7.1	9.2	9.2
	02 Spacer block		4.3	4.3	4.3
	03 Ground levelling layer		0	0	0
	04 Filling of the technological gaps		0	0	0

Tab. 19 Estimated prices of the VY 01.03 components

	Total price of the subvariant for one disposal location		
	VVER 440	VVER 1000	NNS
	CZK thousand	CZK thousand	CZK thousand
01 Blocks + pelletised material (preferred subvariant)	152	180	180
02 Pelletised material	148	175	175

5.4 VY 02.01 Backfilling of the loading corridor

5.4.1 Component details

Name	Backfilling of the loading corridor
Description	Backfilling of the loading corridor - vertical WDP disposal method
Location in the DGR	Loading corridor
Applicability conditions	• Clean excavation without significant disturbances or active water inflows (the exact criteria will be specified in the future) • No materials must be introduced into the disposal borehole or loading corridor (e.g. remnants of linings, ground levelling, etc.)
Subvariants	01 Backfilling of the loading corridor excavated via the TBM method 02 Backfilling of the loading corridor excavated via the NRTM method
Material	Bentonite
Subcomponents	01 Backfilling of the loading corridor with pelletised material For the closure of the corridor see VY 06.02 - Loading corridor operational plug
Production/preparation technology	Industrially processed bentonite in the form of pelletised material
Installation/construction technology	01 Backfilling pneumatically or by mechanical conveyor (screw conveyor), in-situ compaction (optional)

5.4.2 Component requirements

5.4.2.1 External requirements and specifications

5.4.2.1.1 Requirements from the 580/2022 report

Technical report 580/2022 (Dohnálková et al., 2022) sets out the following requirements for the backfilling of the loading corridor and related components.

Corridor:

The dimensions and zone of influence of the loading corridor will depend on the excavation method applied (Grünwald et al., 2018)

	Conventional excavation	TBM excavation
Corridor height	6,700 mm	7,250 mm
Corridor width	4,000 mm	7,250 mm
Zone of excavation influence	2,000 mm	1,000 mm

Backfill:

Proposed backfill parameters:

- ρ_d (whole of the barrier): 1,400 kg/m^3
- Moisture content following emplacement: this value has not yet been determined
- Form: pellets
- Pellet parameters:
  - ρ_d: above 2,000 kg/m^3
  - Moisture content: this value has not yet been determined
  - Granularity: not yet determined

5.4.2.2 Required safety and technical functions

The conceptual design of the backfill is based on the safety and technical functions that it is required to provide, which can be divided into the following categories:

- Ensure the stability of the buffer (against excessive swelling)
- Prevent the transport of water and aggressive materials
- Minimisation of the transport of, and the retardation of, radionuclides
- Ensure the removal of generated gases
- Ensure the removal of heat
- Prevent the creation of preferential pathways

The backfill material must ensure that there is no excessive displacement of the material from the disposal borehole (sufficient support against the swelling of the buffer). Furthermore, it must ensure that the transport of water and radionuclides through the backfill is minimised. At the same time, however, it must allow for the drainage of gases from the buffer without impairing the function of the backfill.

In general, it can be stated that similar general requirements apply to the backfill as to the buffer (see chapter).

5.4.3 Component design assumptions

The conceptual design is based on:

- the required dimensions as set out in the 580/2022 report (Dohnálková et al., 2022)
- the anticipated interactions as described in the 616/2022 report (Večerník et al., 2022)
- the requirements concerning the safety functions as set out in the 618/2022 report (Pospíšková et. al., 2022)
- technical feasibility
- economic feasibility

The requirements for the properties of the bentonite are listed in Tab. 6, chapter 3.1

5.4.4 Component description

The loading corridor (DuSO 08) refers to the underground corridor located in the disposal horizon in which the disposal boreholes (DuSO 09) are situated. The corridor will be used for transport purposes during the WDP loading phase. Once the disposal boreholes in the loading corridor have been filled, the corridor will be backfilled and sealed with a plug.

The backfilling of the loading corridor according to the 580/2022 report (Dohnálková et al., 2022) will comprise bentonite pellets.

The loading corridor according to the vertical disposal concept can be excavated via two methods, i.e. conventionally applying the NRTM method or mechanically using the TBM approach.

Thus, two options exist concerning the backfilling procedure:

- 01 Backfilling of the loading corridor excavated via TBM (Fig. 8)
- 02 Backfilling of the loading corridor excavated via NRTM (Fig. 9)

From the point of view of the backfilling procedure, these options are identical. The only difference will concern the geometry of the space to be filled (according to the excavation technology selected).

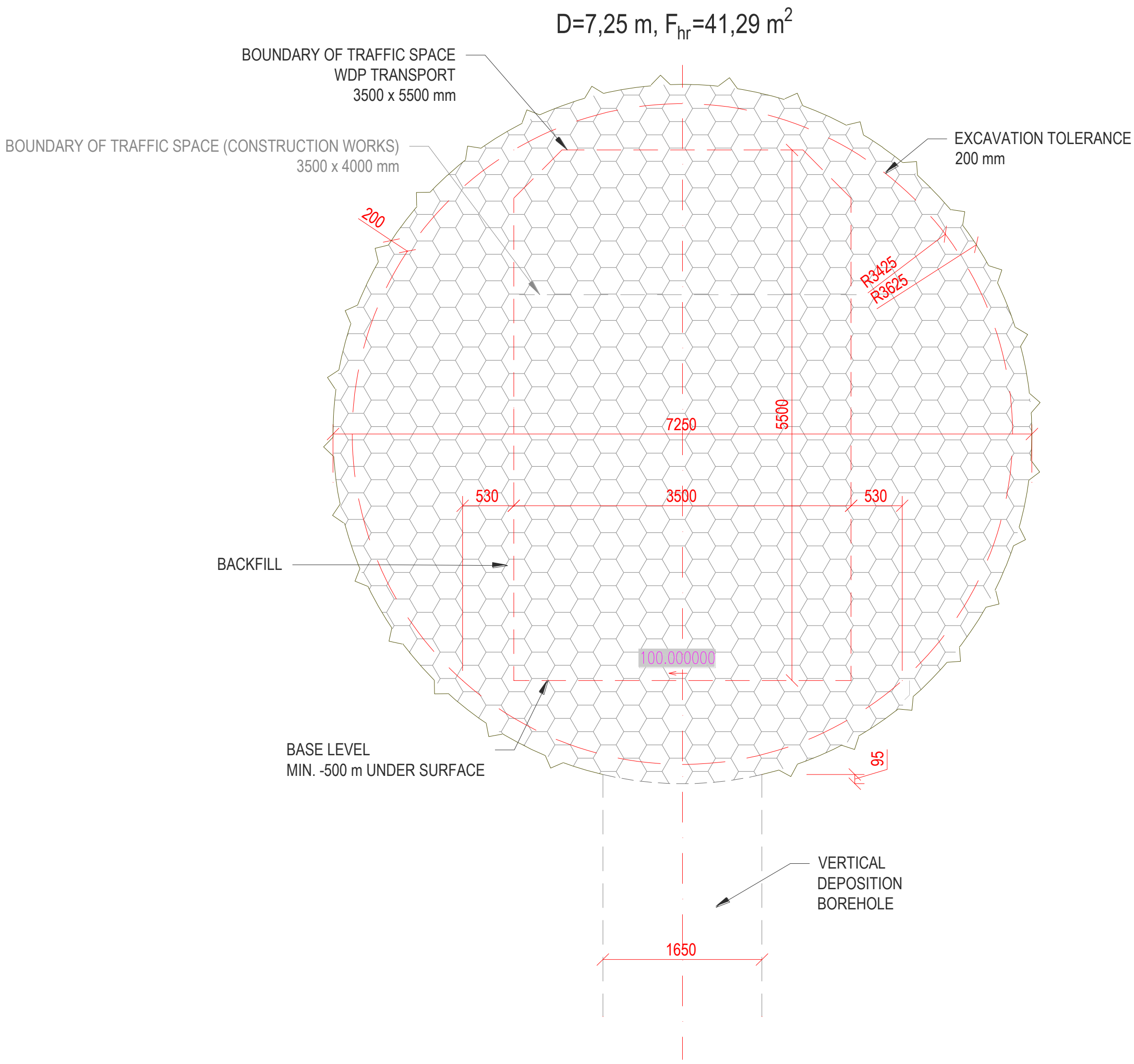

Fig. 8 Backfilling of the loading corridor - option 01 TBM

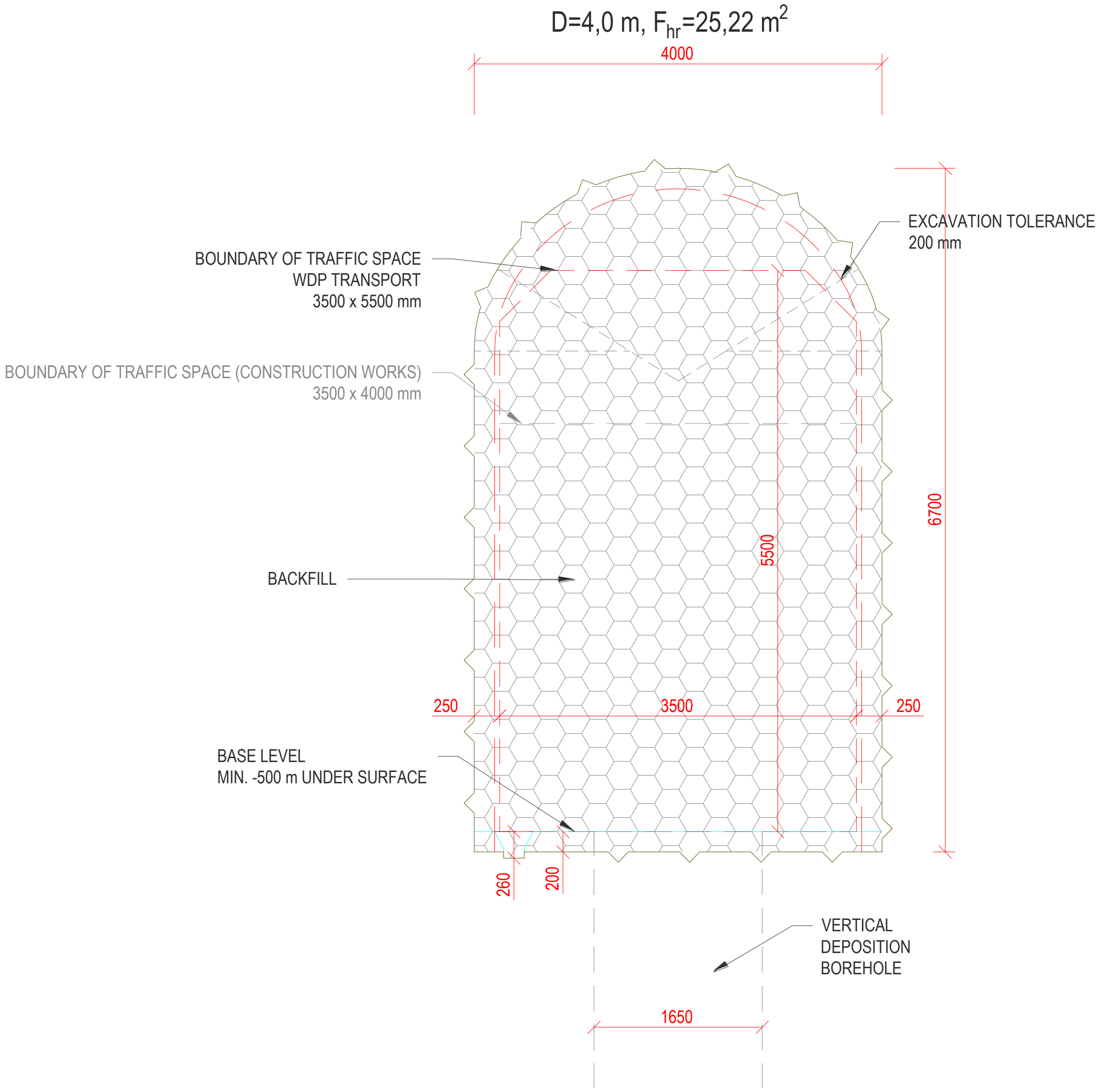

Fig. 9 Backfilling of the loading corridor - option 02 NRTM

5.4.5 Locations of applicability in the DGR

Primary use: disposal corridor backfilling - vertical system. Construction entity DuSO 08.

Secondary use: other spaces in the disposal horizon apart from the RAW disposal chambers.

5.4.6 Applicability conditions

- Clean excavation without significant disturbances or active water inflows (the exact criteria will be specified in the future)
- No materials must be introduced into the loading corridor (e.g. remnants of linings, ground levelling, etc.) that could negatively affect the safety of the DGR

5.4.7 Subvariants and the subcomponents thereof

The two proposed options are technologically identical and will differ only in terms of the geometry of the loading corridor. In both cases, the filling will consist of pelletised material with an average ρ_d following disposal of 1,400 kg/m^3 and will be the same as for the whole of the loading corridor, which will be terminated with an operational plug, see component VY 06.02.

5.4.8 Production/preparation technology

Industrially mined and processed (homogenised) bentonite will be used for the backfill. It will be supplied by the manufacturer in the pelletised form with a suitable granular composition. The material will then be stored under suitable conditions until the time of use.

The pelletised material will not need to be modified before use and will be transported to the disposal location in suitable transport containers.

5.4.9 Installation/construction technology

Prior to the actual installation of the backfill, it will be necessary to ensure that no other materials have been introduced into the loading corridor (e.g. lining remnants, ground levelling, etc.). If such materials remain in the corridor, it will be necessary to assess in advance whether they will affect the safety of the DGR.

The excavation process must be without significant disturbances or active water inflows (the exact criteria will be specified in the future)

The installation process will be via mechanical means. The filling machine will use pneumatic and/or mechanical transport (belts, screw conveyor) methods to transfer the pelletised material from the transport containers to the disposal site. If necessary, the machine will ensure any necessary corridor reinforcement requirements and/or vibratory compaction during the transfer process. It is assumed that the loading corridor will be gradually filled from the pre-closed end in the direction towards the future operational plug.

5.4.10 Estimation of unit prices

The estimation of the prices of bentonite-based backfilling is based on the prices stated in the 134/2017 report (Grünwald et al., 2018) and increased in line with the inflation rate in the period 2018-2022. The price determination procedure is described in chapter 4.2. Tab. 20 shows the cubic capacity of the material used to calculate the prices and the resulting costs. The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 20 Estimated prices of the VY 02.01 components

	Bentonite ρ_d [kg/m^3]	Cross-section [m^2]	Price [CZK thousand per m length]
01 Backfilling of the loading corridor excavated via TBM	1,400	41.3	468
02 Backfilling of the loading corridor excavated via NRTM		25.22	286

5.5 VY 03.01 Backfilling of the RAW chambers – whole chamber

5.5.1 Component details

Name	Backfilling of the RAW chambers
Description	Stabilisation backfill
Location in the DGR	RAW chambers
Applicability conditions	The type of RAW to be disposed of will influence the choice of the backfilling material The location of the RAW chamber (disposal level/distance from the SNF disposal section) will influence the choice of the backfilling material. The RAW chambers must be located in places without active water inflows. The RAW chambers must, if possible, contain a minimum of introduced materials (linings, reinforcement meshing, grouting)
Subvariants	01 Cement backfilling 02 Bentonite backfilling
Material	According to the subvariants
Subcomponents	01 Chamber backfill 02 Venting/borehole backfill Note: Chamber closure, see VY 06.03. Operational plug for the RAW chambers
Production/preparation technology	01 Cement backfilling - industrially processed 02 Bentonite backfilling - industrially processed according to requirements (pellet form and crushed to form a loose mixture or in the form of blocks of the required size)
Installation/construction technology	Backfilling of the whole chamber with a liquified or loose mixture, compaction of the loose mixture; installation of the plug.

5.5.2 Component requirements

5.5.2.1 External requirements and specifications

RAW that does not meet the conditions of acceptability for disposal at the Bratrství, Richard and Dukovany repositories will be disposed of in RAW chambers in the DGR. This RAW concerns primarily waste that contains radionuclides with long half-lives. It will comprise RAW that is currently stored at the Richard repository, part of the waste from the decommissioning of nuclear facilities and the residue from the reprocessing of SNF from the LVR-15 research reactor. Currently, unprocessed SNF from the LVR-15 reactor is also included in this group (Touš et al., 2017 and Touš et al. 2018); however, due to its characteristics and radionuclide composition, this type of RAW would be more suitably disposed of in the SNF disposal horizon.

5.5.2.1.1 Requirements related to the 580/2022 report (Dohnálková et al. 2022)

A system of caverns - disposal chambers - will be created for the disposal of this RAW. The waste will be packed into WDPs, which will be emplaced in the chambers. Once filled, the chambers will be stabilised with the backfilling material. The chambers will then be permanently closed with plugs.

The disposal chambers will comprise conventionally excavated mine workings located in part of the underground section of the DGR complex that will be earmarked for the disposal of RAW other than SNF. The design parameters of the disposal chambers are:

- Length: 55,000 mm
- Width: 10,500 mm
- Height: 4,800 mm
- Number of chambers in the DGR: 18

The filling material of the chambers is intended for the final backfilling of the chambers prior to their closure. The form of the material must be such that it ensures the long-term stabilisation of the waste packages. The exact design parameters of this component have not yet been determined.

The 580/2022 report (Dohnálková et al. 2022) does not specify any more detailed parameters or requirements for the location of the RAW disposal chamber horizon.

5.5.2.2 Required security and technical functions

The conceptual design for the backfilling of the RAW chambers is based on the safety and technical functions that it will be required to provide. These can be divided into the following categories:

- Prevention of the access of water and aggressive materials to the WDP

The backfilling of the RAW chambers must delay for the maximum time possible the moment at which water reaches the WDP and, subsequently, the disposed of RAW. The presence of groundwater triggers chemical reactions that result in the degradation of the engineered barriers. This function is influenced by the density of the material, its hydraulic properties and its strength (the thickness of the barrier).

- Retardation properties and the limitation of radionuclide migration

Following the penetration of water into the disposed of RAW, it provides a potential medium for the transport of radionuclides. The selection of the most suitable material properties will act to retard the progress of radionuclides through the engineered barrier due to the initiation of chemical reactions. This function is influenced by the mineral composition and porosity of the material, the hydraulic properties of the material and its strength (the thickness of the barrier).

- Mechanical protection of the WDP

The backfilling material of the RAW chambers will also have a mechanical function. It will fill the empty spaces in the chambers and, thus, ensure their mechanical stability. In the case of external events, it will ensure that the WDPs remain fixed in position. This function is influenced by the strength and deformation characteristics of the material.

- Heat dissipation (for HLW)

Since untreated SNF from the LVR-15 reactor is currently also included in this group of RAW, the backfill material will have to ensure the removal of the heat generated so as to avoid the occurrence of a critical condition due to overheating. This function is influenced by the thermal conductivity, specific heat capacity and strength (the thickness of the barrier) of the material.

- Chemical compatibility with the material of the WDP (no acceleration of its degradation)

Chemical changes lead to the degradation of the backfill material and the loss of its original properties. This process is influenced by the chemical and mineralogical composition, groundwater composition, microbial composition and its development over time and the disposal conditions.

- Ability to allow for the removal of gases

The backfill material must also allow for the removal of generated gases and prevent an increase in pressure in the engineered barrier system as a whole. This function is influenced by the chemical and mineralogical composition of the backfill and its density.

The various safety and technical functions of the component listed above will be potentially threatened by the activity of microorganisms. The development of microbial activity can be expected mainly in places in the bentonite with a lower bulk density and at the interfaces between the bentonite and other materials. The compaction of the bentonite and the limiting of both the creation of voids and the content of organic substances in the bentonite that could serve as a source of energy for such microorganisms will contribute to limiting the extent of the microbial activity (see chapter 3.1). The natural development of microbial activity in cement backfill is limited mainly by the high pH of the material; thus, in the case of low-pH concrete it will also be necessary to take into account the development of microbial activity (see chapter 3.2). Other materials that have been left in the chambers, e.g. lining remnants, reinforcement meshing and grouting may act to support the unwanted activity of microorganisms. The backfilling of the RAW chambers may thus be threatened by processes such as the bio-deterioration of the concrete, the microbiologically influenced corrosion of the steel materials and the consumption of organic substances from grouting materials, which will lead to the further development of microbial activity (for more information on interaction processes, see the 616/2022 report, Večerník et al., 2022). Hence, we strongly recommend the minimal use of other materials in the chambers or their removal prior to the closure of the repository (if technically possible).

5.5.3 Component design assumptions

The conceptual design is based on:

- the required dimensions as set out in the 580/2022 report (Dohnálková et al., 2022),
- the anticipated interactions as described in the 616/2022 report (Večerník et al., 2022),
- the requirements concerning the safety functions,
- technical feasibility,
- economic feasibility.

5.5.4 Component description

The component comprises the backfilling of the RAW disposal chambers. The location, geometry and other properties of the backfill will be determined by the requirements and design parameters of the RAW disposal chambers.

Grünwald et al. (2018) and Pospíšková et al. (2011) set out the dimensions of the RAW disposal chambers as: 10.5 m wide and 55 m long. At full width, the chamber will be 47.9 m long; it then narrows to a width of 5.6 m at the mouth. The height clearance of the chambers will be 4.95 m.

The RAW disposal chambers will be excavated conventionally and will be connected via a corridor to the loading tunnel. The lining of the chambers and the connecting corridors (where necessary) will consist of shotcrete with reinforcement meshing. The floor will be levelled with a layer of ordinary concrete.

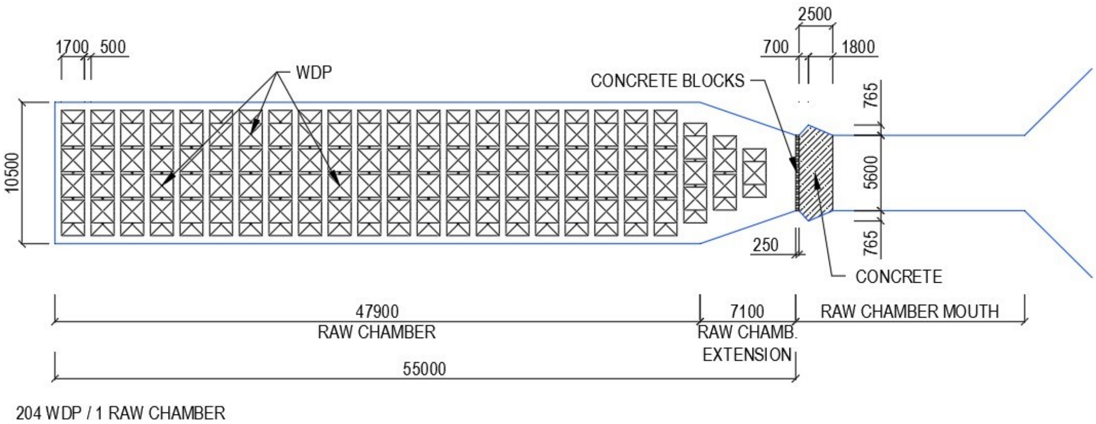

Fig. 10 RAW disposal chamber - layout

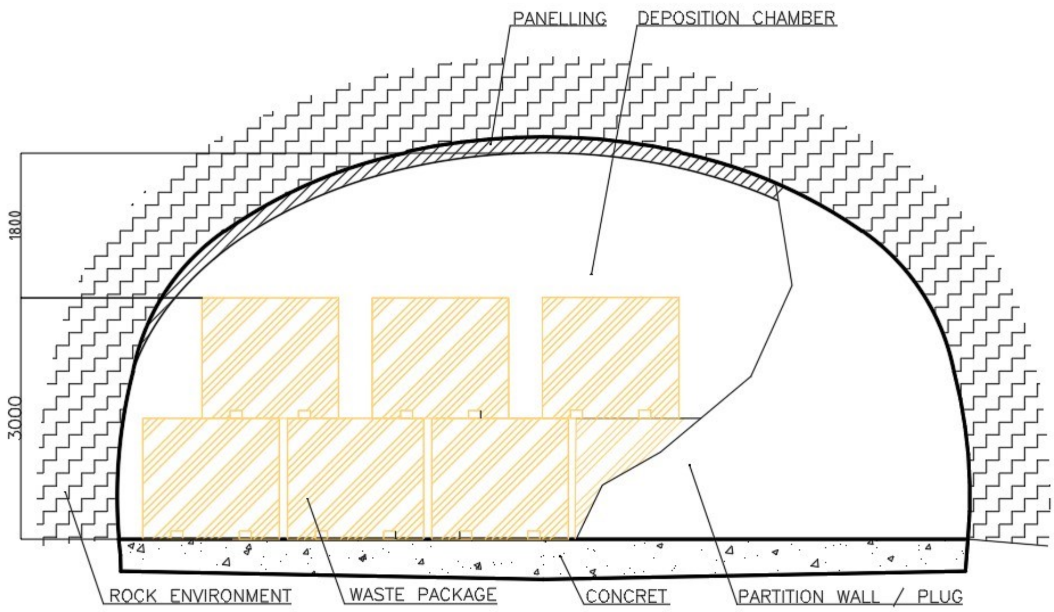

Fig. 11 RAW disposal chamber – cross-section

The component is divided into two subcomponents, the division of which is based on the functions of the subcomponents and their properties:

- 01 Chamber backfilling see chapter 5.12
- 02 Venting/borehole backfilling

The various subcomponents are described in more detail in chapter 5.5.7.

5.5.5 Locations of applicability in the DGR

This component applies only to the RAW disposal chambers (DuSO 11).

Pospíšková et al. (2011) proposed that the RAW (other than SNF) disposal horizon be placed at the same level as the SNF disposal section. Since it is assumed that one of the potential backfill materials will be cement-based, the location of this section was subsequently re-evaluated since the assumed volumes of backfilling material and the relatively small distance from the SNF disposal sections could exert a significant negative impact on the bentonite that will be used as the buffer material that will surround the WDPs with SNF.

Subsequently, a concept that considered a separated RAW disposal horizon was adopted in studies on the layout of the DGR (e.g. Špinka et al. (2018) or Bureš et al. (2018)). The boundary conditions were set as follows:

- Disposal of the RAW in a horizon with an overburden of a min. of 300 m;
- Disposal of the RAW in a horizon of a min. of 50 m above the SNF disposal horizon;

- Disposal of the RAW in places in which the immediate vicinity of potentially usable rock blocks and the loading tunnel are first reached (subject to the validity of the above-mentioned conditions).

Currently (report 580/2022, Dohnálková et al., 2022), it has not been clearly determined where the chambers will eventually be constructed. The decision on the optimal location of the RAW chambers will be influenced by:

- The disposal inventory (the majority radionuclides and their properties, including their radiotoxicity);
- The form of the RAW (the RAW material and the use/non-use of a matrix);
- The properties of the backfill material in the RAW chambers (the material itself and its compatibility with the other components of the DGR, including the WDP).

5.5.6 Applicability conditions

The chambers must be located in a rock mass without the significant inflow of groundwater so as to prevent premature chemical and microbiological degradation and the mechanical destruction of the backfill material.

The chambers will have to be reinforced; however, since it is supposed that the reinforcement components will not be removed due to the RAW disposal method envisaged (loading of the whole of the chamber and the backfill), they must, where possible, contain a minimum of supplementary materials (linings, reinforcement meshing, grouting). This means that such materials will be used only where absolutely necessary.

In order to limit the amount of materials that it will not be possible to remove before backfilling the RAW chambers, the disposal area can be adjusted as follows:

In the case of the use of a cement-based backfill, floors will be laid in the RAW chambers, the composition of which will be required to fully correspond to its purpose of use and be as similar as possible to the composition of the applied backfill.

In the case of the use of a bentonite-based backfill, a levelling layer of sufficient thickness and of a suitable material composition will be applied so as to meet the requirements for the stable disposal of the RAW (primarily with concern to the weight of the WDPs and interaction with the component – the chamber backfill material).

The choice of the backfill material will be influenced by the disposed of RAW and its properties, as well as the materials used for the construction of the WDPs and the matrix used for the stabilisation of the RAW in the WDP.

The choice of the backfill material will also be influenced by the disposal location in relation to the SNF disposal areas (the disposal level/distance from the SNF disposal section).

5.5.7 Subcomponents (geometry, required material and properties)

5.5.7.1 Subcomponent 01 – Chamber backfill

The basic properties of the subcomponent are:

- Its geometry (see chapter 5.5.4 for details)
- The material and its properties (see chapter 3 for details)
- Lifetime
- Availability in the required quantity
- Workability (see chapter 5.5.8 for details)
- Price (see chapter 5.5.10)

The location, geometry and other properties will be determined by the requirements and design parameters of the RAW disposal chambers.

Current waste characterisation and legislative requirements indicate that the Czech disposal concept includes both waste containing fissile elements (stored nuclear material) and waste containing long-term radionuclides (primarily waste from the decommissioning of nuclear facilities) in this RAW category. Therefore, the backfill material used must correspond to these requirements.

With respect to the types of RAW to be disposed of, it is recommended that bentonite be used as the backfill material for waste containing fissile radionuclides.

A cement-based material could be used as the chamber backfill for RAW containing long-lived radionuclides. However, in the event that the RAW chambers are located near to the SNF disposal sections, it will be essential to take into account the potential negative influence on the bentonite that will be used for the buffer surrounding the WDPs containing SNF. A report by Večerník et al. (2022) provides a detailed evaluation of the mutual influences of cementitious materials and bentonite.

A report by Pospíšková et al. (2022) describes the results of research into the approaches of other countries to the disposal of such types of waste. The results of the research revealed, *inter alia*, that bentonite is used as the backfill material for reprocessed waste, whereas backfilling materials based on cement, bentonite, crushed rock or a mixture of these materials are used for the backfilling of RAW containing long-term radionuclides.

In accordance with the above information, two subvariants were proposed depending on the material used – bentonite or cement backfilling.

The service life of the component will be determined by the properties of the material used and its composition.

5.5.7.1.1 01 Cement backfill

For a more detailed specification of the required material and its properties, see chapter 3.2.1.

5.5.7.1.2 02 Bentonite backfill

For a more detailed specification of the required material and its properties, see chapter 3.1.

The parameters of the bentonite backfill will be identical to component VY 01.01.

The backfilling of the RAW chambers can be applied in two ways:

- In the form of a loose mixture (pelletised material);
- In the form of blocks and the filling of the remaining free spaces with pelletised material. The blocks will be pre-assembled into layers/units and stored in layers/units. The

system applied for the division of the layers into individual blocks and the height of the layer will form the subject of further research.

The backfilling of the RAW chambers will be required to have an average ρ_d following disposal of 1,600 kg/m^3.

Note: This value cannot currently be reliably ensured for pelletised material. Further technical research and development is required in this area. Once the technological issues have been solved, it is advisable to switch to this option.

The average value of the density of the bentonite in the RAW chambers (ρ_d = 1,600 kg/m^3) will be used to calculate the unit price for the component.

Identical to VY 06.03. See chapter 5.12

5.5.7.2 Subcomponent 02 - Venting/borehole backfill

Boreholes will be filled with the backfill material. They will be closed using a cement plug.

5.5.8 Production/preparation technology

5.5.8.1.1 01 Cement backfill

Industrially processed concrete will be used (for the properties see chapter 3.2.1).

The transport distance and the total transport time will be taken into account (generally a maximum of 60 min.) during the preparation of the mixture and its subsequent transport to the place of use.

5.5.8.1.2 02 Bentonite backfill

<u>The backfilling concept will be similar to VY 01.</u>

<u>Loose mix (pelletised material)</u>

An industrially processed bentonite mixture in the form of pellets will be used. The pelletised bentonite will have a minimum average ρ_d following disposal of 1,600 kg/m^3.

<u>Blocks and pelletised material</u>

An industrially processed bentonite mixture will be used. The density of the blocks will be ρ_d = 1,700 kg/m^3. The pelletised bentonite will have a minimum average ρ_d following disposal of 1,400 kg/m^3.

Since the size of the blocks and thus the volume to be filled with pelletised bentonite is not currently known, the condition applies that the backfilling of the RAW chambers must reach an average ρ_d following disposal of 1,600 kg/m^3.

An average value of density of the bentonite in the RAW chambers of ρ_d = 1,600 kg/m^3 will be used to calculate the unit price for the component.

5.5.9 Installation/construction technology

With regard to the approach to the backfilling of the RAW chambers and the various structural elements (linings, reinforcement rock bolts, soil) following the backfilling of the RAW chambers, it is assumed that the structural elements will not be removed before closure.

5.5.9.1 01 Cement backfill

The installation of the component, i.e. the backfill, will be conducted according to the proposal in the DGR reference project of 2011 (Pospíšková et al., 2011). The chambers, once filled with RAW, will be filled with a cement-based mixture, which will be transported to the chamber via a temporary pipe inserted into the ventilation corridors located above the chambers. The application of this system will ensure the required compaction of the backfill mixture in the chambers and their ventilation. The size chosen for the segment to be backfilled and the number and location of the filling and venting pipes will have to ensure the seamless backfilling of the RAW WDPs. The flow of the concrete mixture from the outlet of the filling pipe must be guaranteed up to a distance of 8 m (MP.38). The number of ventilation corridors will be determined so as to correspond to this requirement.

A temporary steel barrier (formwork) will be installed at the mouth of the chamber at which a reinforced concrete frame and vaulting will be constructed. This will be removed following the backfilling of the chamber with the cement mixture. Openings will be built into the temporary formwork that will be used for the transport of the backfill to the mouth of the chamber, including compaction equipment, ventilation and monitoring. These openings will subsequently be sealed. The chamber thus backfilled will then be permanently sealed with an operational plug

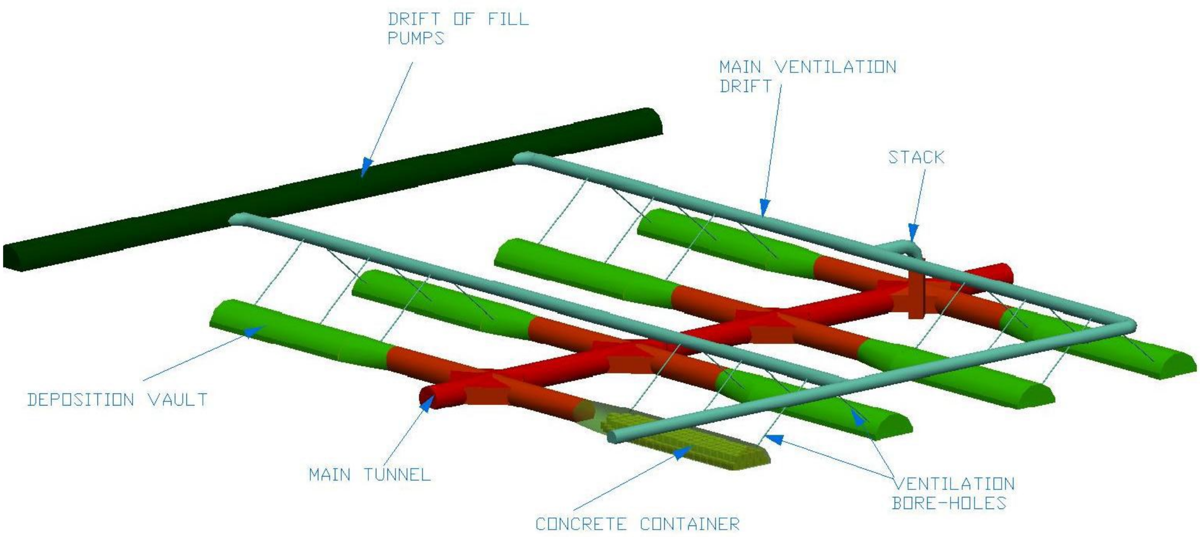

Fig. 12 Approach to the backfilling of the RAW chambers with a cement mixture

5.5.9.2 02 Bentonite backfilling

The transport of the bentonite backfill in the form of pellets to the RAW chambers will proceed from the loading corridor. Bentonite compaction will be carried out section by section according to the approach to the filling of the chambers with RAW WDPs.

It is assumed that loading and compaction will be carried out in the horizontal direction up to the mouth of the chamber, at which the chamber operational plug will be installed.

In the case of the use of bentonite blocks, the RAW WDPs will be surrounded by blocks and the resulting free space will be filled with pelletised bentonite.

The blocks will be pre-assembled in layers and stored layer by layer. The system used for dividing the layers into individual blocks and the height of the layers will form the subject of further research.

Loading and compaction will be carried out in the horizontal direction up to the mouth of the chamber, at which the chamber operational plug will be installed. The ventilation openings will be filled and sealed.

5.5.10 Estimation of unit prices

The estimation of the prices of the cement backfill is based on an expert estimation and experience from similar facilities (the Richard and Bratrství repositories). The unit price of the material includes its preparation and installation.

The estimation of the prices of bentonite-based backfilling is based on the prices stated in the 134/2017 report (Grünwald et al., 2018) and increased in line with the inflation rate in the period 2018-2022. The price determination procedure is described in chapter 4.2.

Summary of the input data for the calculation of the volume of the component - backfill (see Fig. 10).

The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 21 Amounts of material required for the VY 03.01 options and estimation of the price of the component

	Amount of material [m^3/chamber]	Total price for one chamber [CZK thousand]
01 Cement backfill	1,700	19,380
02 Bentonite backfill	1,700	21,974

5.6 VY 03.02 Backfilling of the RAW chambers – section-by-section filling of the chambers

5.6.1 Component details

Name	Backfilling of the RAW chambers
Description	Stabilisation backfill
Location in the DGR	RAW chambers
Applicability conditions	The type of RAW to be disposed of will influence the choice of the backfilling material The location of the RAW chamber (disposal level/distance from the SNF disposal section) will influence the choice of the backfilling material. The RAW chambers must be located in places without active water inflows. The RAW chambers must, if possible, contain a minimum of introduced materials (linings, reinforcement meshing, grouting)
Subvariants	01 Cement backfill 02 Bentonite backfill
Material	According to the subvariant
Subcomponents	01 Chamber segment partition wall (lost formwork, anchoring elements) 02 Chamber backfill 03 Ventilation pipe 04 Backfill in the ventilation pipe Note: Chamber closure, see VY 06.03. Operational plug for the RAW chambers
Production/preparation technology	01 Cement backfilling - industrially processed 02 Bentonite backfilling - industrially processed according to requirements (pellet form and crushed to form a loose mixture or in the form of blocks of the required size)

Installation/construction technology	Preparations for backfilling; the backfilling of segments with a liquified or loose mixture, compaction of the loose mixture; installation of the plug

5.6.2 Component requirements

5.6.2.1 External requirements and specifications

Identical to component 03.01 - Filling of the RAW chambers - complete filling (see chapter 5.5.2.1) and the Requirements of the 580/2022 report (Dohnálková et al. 2022), see chapter 5.5.2.1.1.

5.6.2.2 Required safety functions

The required safety functions are the same as for component 03.01 – Filling of the RAW chamber - complete filling (see chapter 5.5.2.2).

5.6.3 Component design assumptions

The prerequisites for the design of the component are the same as for component 03.01 - Filling of the RAW chamber – complete filling (see chapter 5.5.3).

5.6.4 Component description

The component comprises the backfilling of the RAW disposal chambers. The location, geometry and other properties of the backfill will be determined by the requirements and design parameters of the RAW disposal chambers.

Grünwald et al. (2018) and Pospíšková et al. (2011) set out the dimensions of the RAW disposal chambers as: 10.5 m wide and 55 m long. At full width, the chamber will be 47.9 m long; it then narrows to a width of 5.6 m at the mouth. The height clearance of the chambers will be 4.95 m.

The RAW disposal chambers will be excavated conventionally and will be connected via a corridor to the loading tunnel. The lining of the chambers and the connecting corridors (where necessary) will consist of shotcrete with reinforcement meshing. The floor will be levelled with a layer of ordinary concrete.

The component has been broken down into subcomponents based on the functions of the various subcomponents and their properties:

- 01 Chamber segment partition wall (lost formwork, anchoring elements)
- 02 Chamber backfill
- 03 Ventilation pipe
- 04 Backfill in the ventilation pipe

5.6.5 Locations of applicability in the DGR

This component applies only to the RAW disposal chambers (DuSO11 according to Grünwald et al., 2018, DuSO26 according to Pospíšková et al., 2011), see chapter 5.5.5.

5.6.6 Applicability conditions

The applicability conditions are identical to those of component 03.01 - Filling of the RAW chamber - complete filling (see chapter 5.5.6).

5.6.7 Subcomponents (geometry, required material and properties)

5.6.7.1 Subcomponent 01 - Chamber segment partition wall (lost formwork, steel anchoring elements)

A reinforced concrete partition wall (lost formwork) be installed in selected locations in the chamber at predetermined intervals. This will serve to create a separated space, i.e. a chamber segment that will then be backfilled.

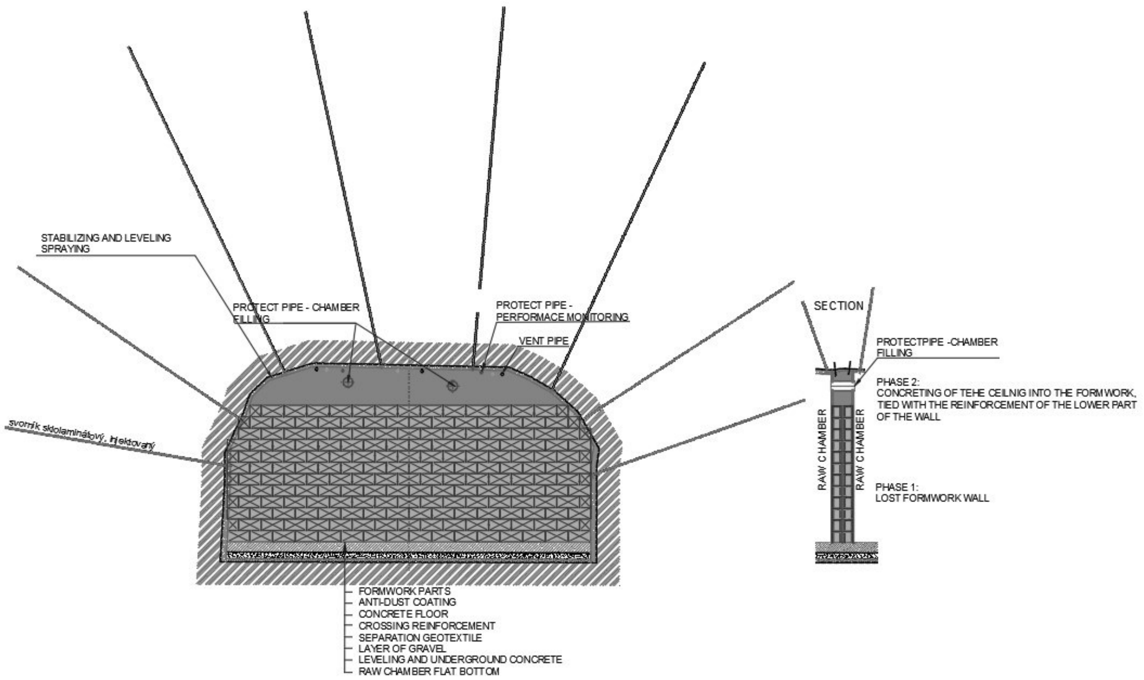

Fig. 13 Separation of a segment - reinforced concrete partition wall (lost formwork).

5.6.7.2 Subcomponent 02 – Chamber backfill

Identical to component 03.01 - RAW chamber backfill - complete filling (see chapter 5.5.7.1).

5.6.7.3 Subcomponent 03 - Ventilation pipe

A ventilation pipe will be installed in the upper part of the separated segment in order to ensure the removal of air from the segment of the RAW chamber.

5.6.7.4 04 Ventilation pipe backfill

Subcomponent 04 - The ventilation pipe will be filled with the backfill material.

5.6.8 Production/preparation technology

Identical to component 03.01 - RAW chamber backfill - complete filling (see chapter 5.5.8).

5.6.9 Installation/construction technology

With regard to the approach to the backfilling of the RAW chambers and the various structural elements (linings, reinforcement rock bolts, soil) following the backfilling of the RAW chambers, it is assumed that the structural elements will not be removed before closure.

5.6.9.1 01 Cement backfill

The spaces filled with RAW WDPs (segment) will be separated from the rest of the chamber by a reinforced concrete partition made of lost formwork incl. reinforcement at predetermined intervals.

The resulting separated space will be filled with a cement mixture, which will be transported to the segment using pipes that penetrate through the reinforced concrete partition.

The size of the segment to be filled and the number and location of the filling and ventilation pipes will be determined in terms of efficiently securing the disposed of WDPs. The flow of the concrete mixture from the outlet of the filling pipe must be guaranteed up to a distance of 8 m (MP.38). Openings in the partition will be used for filling, ventilation and monitoring purposes.

In order to ensure the maximum homogeneity of the cement filling, the maximum length of the segments will be limited to approx. 15-25 m. The flow of the concrete mixture from the outlet of the filling pipe must be guaranteed up to a distance of 8 m (MP.38).

A reinforced concrete partition made from lost formwork will then be built at the mouth of the chamber fitted with an inspection opening or other openings that can be used to transport the backfill to the mouth of the chamber; they can also be used for the access of compaction equipment and ventilation and monitoring purposes. All these openings will subsequently be sealed. Each chamber will then be permanently sealed with an operational plug.

5.6.9.2 Bentonite backfill

The transport of the bentonite backfill in the form of pellets to the RAW chambers will proceed from the loading corridor. Bentonite compaction will be carried out section by section according to the approach to the filling of the chambers with RAW WDPs.

If bentonite blocks are used, the disposed of WDPs in the individual segments will be lined with these blocks and the resulting free spaces will be filled with pelletised bentonite.

The blocks will be pre-assembled in layers and stored layer by layer. The system used for dividing the layers into individual blocks and the height of the layers will form the subject of further research.

Loading and compaction will be carried out in the horizontal direction up to the mouth of the individual segments, where a separating wall will be installed. An operational plug will then serve to seal the mouth of the chamber.

5.6.10 Estimation of unit prices

The estimation of the prices of the cement backfill is based on an expert estimation and experience from similar facilities (the Richard and Bratrství repositories). The unit price of the material includes its preparation and installation.

The estimation of the prices of bentonite-based backfilling is based on the prices stated in the 134/2017 report (Grünwald et al., 2018) and increased in line with the inflation rate in the period 2018-2022. The price determination procedure is described in chapter 4.2.

Summary of the input data for the calculation of the volume of the component - section-by-section filling (see Fig. 14).

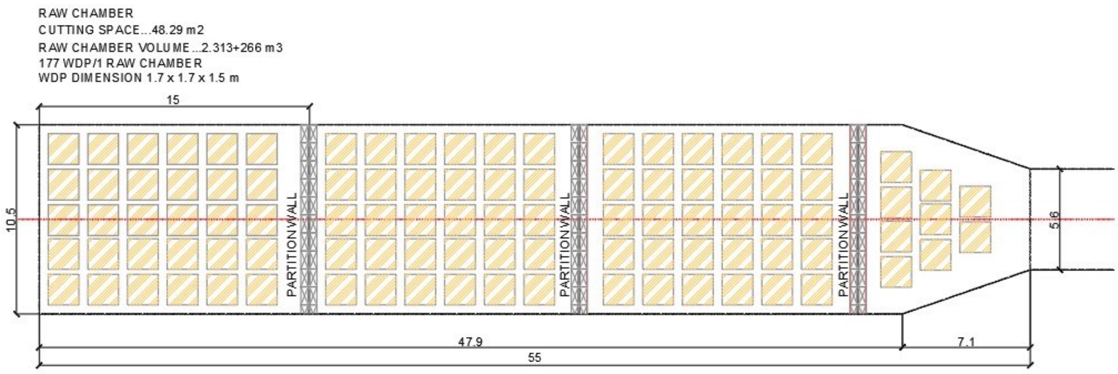

Fig. 14 A RAW chamber with partition walls

The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 22 Amounts of material required for the VY 03.02 options and estimation of the price of the component

	Amount of material [m^3/chamber]	Total price for one chamber [CZK thousand]
01 Cement backfilling	1,700	21,003
02 Bentonite backfilling	1,700	23,612

5.7 VY 04.01 Backfilling of the spaces in the disposal horizon

5.7.1 Component details

Name	Backfilling of the spaces in the disposal horizon
Description	Backfill material
Location in the DGR	Main corridors, technical facilities of the underground part of the DGR (corridors, caverns)
Applicability conditions	• Clean excavation without active water inflows (the exact criteria will be specified in the future) • Removal of equipment in the main corridors and technical facilities of the underground part of the DGR (corridors, caverns). Spaces with a minimum amount of introduced materials. *The permitted amount of introduced materials will be specified in future*
Subvariant	01 Pelletised material
Material	Bentonit
Subcomponents	01 Pelletised material backfill Note: Chamber closure, VY 06.04 Plug – Operational plug in the disposal horizon
Production/preparation technology	Industrially processed bentonite in the form of pellets
Installation/construction technology	01 Backfilling using pneumatic or mechanical conveyor (screw conveyor) methods; on-site compaction (optional)

5.7.2 Component requirements

The requirements are the same as for component 02.01 (see chapter 5.4.2); the only differences are that no emphasis is placed on the dissipation of heat and the backfill does not ensure the stability of the buffer against swelling.

5.7.3 Component design assumptions

The assumptions are identical to those of component 02.01. See chapter 5.4.3.

5.7.4 Component description

VY 04.01 comprises an engineered barrier made of compacted bentonite located in the main corridors and technical facilities of the underground part of the DGR (corridors, caverns). Technically and technologically, it is identical to the backfill of the loading corridor (VY 02.01). See chapter 5.4.4.

5.7.5 Locations of applicability in the DGR

Primary use: Backfilling of the spaces in the disposal horizon with the exception of the disposal boreholes, loading corridors and RAW chambers. Construction entities DuSO 01-03, 05, 06, 07, 10, 12-22.

5.7.6 Applicability conditions

- Clean excavation without active water inflows (the exact criteria will be specified in the future)
- Removal of equipment in the main corridors and technical facilities of the underground part of the DGR (corridors, caverns). Spaces with a minimum amount of introduced materials. *The permitted amount of introduced materials will be specified in future*

5.7.7 Subvariants and their subcomponents

Identical to those of component VY 02.01. See chapter 5.4.7.

5.7.8 Production/preparation technology

Identical to those of component VY 02.01. See chapter 5.4.8.

5.7.9 Installation/construction technology

Identical to those of component VY 02.01. See chapter 5.4.9.

5.7.10 Estimation of unit prices

The estimation of the prices of bentonite-based backfilling is based on the prices stated in the 134/2017 report (Grünwald et al., 2018) and increased in line with the inflation rate in the period 2018-2022. The price determination procedure is described in chapter 4.2. Tab. 23 - Tab. 29 show the cubic capacity of the material used to calculate the prices and the resulting costs. The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 23 Amounts of material required for the DuSO 01, 02, 03, 05 options

		DuSO 01	DuSO 02	DuSO 03	DuSO 05
	Corridor excavation method	Cross-section [m^2]	Cross-section [m^2]	Cross-section [m^2]	Cross-section [m^2]
Vertical disposal	TBM mechanised mining method	41.29	41.29	38.48	41.29
	Conventional mining method	36.32	36.32	38.48	29.23
Horizontal disposal	TBM mechanised mining method	38.48	38.48	38.48	38.48
	Conventional mining method	36.32	36.32	38.48	29.23

Tab. 24 Amounts of material required for the DuSO 10, 12, 18 options

			DuSO 10	DuSO 12	DuSO 18
	Prevailing corridor excavation method	Bentonite ρ_d [kg/m^3]	Cross-section [m^2]	Cross-section [m^2]	Cross-section [m^2]
Vertical disposal	TBM mechanised mining method	1,400	100	98.4	40
	Conventional mining method		100	80.4	40
Horizontal disposal	TBM mechanised mining method		120	58.8	40
	Conventional mining method		120	58.8	40

Tab. 25 Amounts of material required for the DuSO 17 option

			Excavation and construction section	Preparation and disposal section
			DuSO 17	
	Prevailing corridor excavation method	Bentonite ρ_d [kg/m^3]	Cross-section [m^2]	Cross-section [m^2]
Vertical disposal	TBM mechanised mining method	1,400	40	40
	Conventional mining method		40	40
Horizontal disposal	TBM mechanised mining method		40	84
	Conventional mining method		40	84

Tab. 26 Estimation of prices: DuSO 01, 02, 03, 05

		DuSO 01	DuSO 02	DuSO 03	DuSO 05
	Corridor excavation method	Component price [CZK thousand/m length of the construction entity]	Component price [CZK thousand/m length of the construction entity]	Component price [CZK thousand/m length of the construction entity]	Component price [CZK thousand/m length of the construction entity]
Vertical disposal	TBM mechanised mining method	468	468	436	468
	Conventional mining method	412	412	436	332
Horizontal disposal	TBM mechanised mining method	436	436	436	436
	Conventional mining method	412	412	436	332

Tab. 27 Estimation of prices: DuSO 10, 12, 18

		DuSO 10	DuSO 12	DuSO 18
	Prevailing corridor excavation method	Component price [CZK thousand/m length of the construction entity]	Component price [CZK thousand/m length of the construction entity]	Component price [CZK thousand/m length of the construction entity]
Vertical disposal	TBM mechanised mining method	1,134	1,116	454
	Conventional mining method	1,134	912	454
Horizontal disposal	TBM mechanised mining method	1,361	667	454
	Conventional mining method	1,361	667	454

Tab. 28 Estimation of prices: DuSO 17

		Excavation and construction section	Preparation and disposal section
		DuSO 17	
	Prevailing corridor excavation method	Component price [CZK thousand/m length of the construction entity]	Component price [CZK thousand/m length of the construction entity]
Vertical disposal	TBM mechanised mining method	454	454
	Conventional mining method	454	454
Horizontal disposal	TBM mechanised mining method	454	953
	Conventional mining method	454	953

Tab. 29 Estimation of prices: VY 04.01 for DUSO 06, 07, 13 - 16, 18-22

Vertical and horizontal disposal, regardless of the prevailing excavation method	Bentonite ρ_d [kg/m^3]	Cross-section [m^2]	Component price [CZK thousand/m length of the construction entity]
DuSO 06	1,400	29.23	332
DuSO 07		29.23	332
DuSO 13 – Pumping station		32	363
DuSO 13 - Sump		50.27	570
DuSO 14		40	454
DuSO 15		40	454
DuSO 16		155	1,758
DuSO 18		40	454
DuSO 19		40	454
DuSO 20		75	851
DuSO 21 - Corridors		14.9	169
DuSO 21 - Chambers		15.9	180
DuSO 22		32	363

5.8 VY 05.01 Backfilling of the spaces above the disposal horizon (medium depth)

5.8.1 Component details

Name	Backfilling of the spaces above the disposal horizon (medium depth)
Description	Backfill material
Location in the DGR	Loading and unloading tunnel, intake shaft Horizon: -200 to -500 m
Applicability conditions	• Clean excavation without active water inflows (the exact criteria will be specified in the future) • Removal of equipment from the loading and unloading tunnel and the intake shaft. *The permitted amount of introduced materials will be specified in future*
Subvariants	01 Bentonite 02 Bentonite and aggregate mixture (preferred variant)
Material	Bentonite, aggregate
Subcomponents	
Production/preparation technology	Industrially processed pelletised bentonite Crushed aggregate of the appropriate fraction mixed with pelletised bentonite
Installation/construction technology	01 Backfilling using pneumatic or mechanical conveyor (screw conveyor) methods; on-site compaction (optional).

5.8.2 Component requirements

The requirements are the same as for component VY 02.01 (see chapter 5.4.2); the only differences are that no emphasis is placed on the dissipation of heat and the backfill does not ensure the stability of the buffer against swelling.

5.8.3 Component design assumptions

The assumptions are identical to those of component VY 02.01. See chapter 5.4.3.

5.8.4 Component description

The backfilling of the loading and unloading tunnel in the -500 – 200 m horizon is technically and technologically similar to the backfilling of the loading corridor (02.01). See chapter 5.4.4.

The difference concerns the potential to use a mixture of bentonite and aggregate as the backfill material, which will result in price reductions and allow for the adjustment of the hydraulic and other characteristics so that they more closely correspond to the surrounding environment.

5.8.5 Locations of applicability in the DGR

Primary use: Backfilling of the spaces above the disposal horizon (medium depth). Construction entities DuSO 01, 02 and 03.

Secondary use: Backfilling of the spaces above the disposal horizon (subsurface).

5.8.6 Applicability conditions

- Clean excavation without active water inflows (the exact criteria will be specified in the future)
- Removal of equipment from the loading and unloading tunnel. *The permitted amount of introduced materials will be specified in future*

5.8.7 Subvariants and their subcomponents

The component has two subvariants that differ only in terms of the materials used.

5.8.8 Production/preparation technology

Identical to component 02.01. See chapter 5.4.8. In the case of the use of a mixture with aggregate, it will be necessary to mix the aggregate with the pelletised bentonite prior to installation. The ratio between the bentonite and the aggregate will be determined in the future based on the requirements set for the hydraulic and technical properties of the mixture.

5.8.9 Installation/construction technology

Identical to component 02.01. See chapter 5.4.9.

5.8.10 Estimation of unit prices

The estimation of the prices of bentonite-based backfilling is based on the prices stated in the 134/2017 report (Grünwald et al., 2018) and increased in line with the inflation rate in the period 2018-2022. The price determination procedure is described in chapter 4.2. The prices for the commercially available materials and components (e.g. concrete, equipment, rock bolts, etc.) are based on the prices listed in the 2022 construction and work classification (OTSKP, 2022).

The price of the bentonite + aggregate filling cannot currently be determined quantitatively since the ratio of the materials is not yet known. Concerning the calculation of subvariant 02 (mixture), a 15% price saving is predicted.

Tab. 30 - Tab. 32 show the cubic capacity of the material used to calculate the prices and the resulting costs. The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 30 Amounts of material required for the various DuSO options

			DuSO 01, DuSO 02	DuSO 03
	Corridor excavation method	Bentonite (+ aggregate) ρ_d [kg/m^3]	Cross-section [m^2]	Cross-section [m^2]
Vertical disposal	TBM mechanised mining method	1,400		38.48
	Conventional mining method		36.32	
Horizontal disposal	TBM mechanised mining method		38.48	
	Conventional mining method		36.32	

Tab. 31 Estimation of the prices of component VY 05.01, bentonite backfill

		DuSO 01, DuSO 02	DuSO 03
	Corridor excavation method	Component price [CZK thousand/m length of the construction entity]	Component price [CZK thousand/m length of the construction entity]
Vertical disposal	TBM mechanised mining method	468	436
	Conventional mining method	412	
Horizontal disposal	TBM mechanised mining method	436	
	Conventional mining method	412	

Tab. 32 Estimation of the prices of component VY 05.01, bentonite + aggregate backfill

		DuSO 01, DuSO 02	DuSO 03
	Corridor excavation method	Component price [CZK thousand/m length of the construction entity]	Component price [CZK thousand/m length of the construction entity]
Vertical disposal	TBM mechanised mining method	398	371
	Conventional mining method	350	
Horizontal disposal	TBM mechanised mining method	371	
	Conventional mining method	350	

5.9 VY 05.02 Backfilling of the spaces above the disposal horizon (subsurface)

5.9.1 Component details

Name	Backfilling of the spaces above the disposal horizon (subsurface)
Description	Backfill material
Location in the DGR	Loading and unloading tunnel, intake shaft Depth: to -200 m
Applicability conditions	Clean excavation without active water inflows (the exact criteria will be specified in the future) Removal of equipment from the loading and unloading tunnel and the intake shaft. *The permitted amount of introduced materials will be specified in future*
Subvariants	01 Backfilling of the unloading and loading tunnel 02 Backfilling of the intake shaft pit
Material	Aggregate
Subcomponents	
Production/preparation technology	Excavation and processing of natural stone via the crushing of larger pieces of rock and subsequent classification into various fractions.
Installation/construction technology	01 Backfilling using pneumatic or mechanical conveyor (screw conveyor) methods; on-site compaction (optional). 02 Backfilling of the intake shaft

5.9.2 Component requirements

5.9.2.1 External requirements and specifications

Closure is the final technological stage of the disposal process. It concerns the backfilling of all the empty spaces in the DGR in the closure phase, which will ensure the long-term isolation of the DGR from the biosphere.

The design parameters of the closure sealing materials are based primarily on the DGR project design and depend on the required safety function and the location and depth in the DGR according to the 580/2022 report (Dohnálková et al., 2022); in this case:

Depth:	Subsurface (to -200 m).
Dry density:	The value has not yet been determined
Permeability coefficient:	The value has not yet been determined
Form:	Aggregate

5.9.2.2 Required safety and technical functions

The required safety and technical functions during the liquidation of the main mine workings via backfilling will be governed by the applicable legislation.

5.9.3 Component design assumptions

The conceptual design is based on:

- The required dimensions as set out in the 580/2022 report (Dohnálková et al., 2022)
- The anticipated interactions as described in the 616/2022 report (Večerník et al., 2022)
- Safety function requirements
- Technical feasibility
- Economic feasibility

5.9.4 Component description

VY 05.02 comprises an engineered barrier made of aggregate that serves for the backfilling of the main mine workings (the unloading and loading tunnel and the intake shaft).

The unloading and loading tunnel for the vertical and horizontal SNF WDP disposal concepts can be excavated in two ways, i.e. conventionally using the NRTM method or mechanically using TBM full-profile excavation machines.

As with the unloading and loading tunnel, the intake shaft in the case of both SNF WDP disposal concepts can be excavated in two ways, conventionally or mechanically.

Hence, two backfilling options have been proposed:

- 01 Backfilling of the unloading and loading tunnel
- 02 Backfilling of the intake shaft

These subvariants are identical in terms of the backfilling approach. However, they differ in terms of the geometry and volume of the space to be backfilled according to the excavation technology and the way in which it is applied.

The backfill material requirements were specified in chapter 3.3. Once all the main mine workings have been backfilled, they will be finally sealed with the DGR closure plug (see component VY 06.06).

5.9.5 Locations of applicability in the DGR

Backfilling of the spaces above the disposal horizon – subsurface (to -200 m). Construction entities: DuSO 01, DuSO 02 a DuSO 03

5.9.6 Applicability conditions

- Clean excavation without active water inflows (the exact criteria will be specified in the future)
- Removal of equipment from the loading and unloading tunnel and the intake shaft. *The permitted amount of introduced materials will be specified in future*

5.9.7 Subvariants and the subcomponents thereof

As previously mentioned, the two proposed subvariants differ in terms of both geometry and volume, as well as the backfilling technology. In both cases, the backfill will consist of aggregate. The main mine workings will be terminated with the DGR closure plug (see component VY 06.05).

5.9.8 Production/preparation technology

As previously mentioned, it is assumed that processed rubble from the construction of the DGR itself will be used as the main source of aggregate. In the case that this backfill material is unsatisfactory for the purpose, crushed mined natural stone aggregate (crushed gravel) created via the crushing of larger pieces of rock and its subsequent classification into various fractions at the quarry will be used.

5.9.9 Installation/construction technology

Prior to the start of the backfilling of the main mine workings, the respective equipment will be removed.

The technology used for the backfilling of the unloading and loading tunnel will be identical to the VY 02.01 component (see chapter 5.4.9).

The complete backfilling of the intake shaft will be conducted in accordance with the applicable legislation.

5.9.10 Estimation of unit prices

The prices for the commercially available materials and components (e.g. concrete, equipment, rock bolts, etc.) are based on the prices listed in the 2022 construction and work classification (OTSKP, 2022). The price of CZK 344/m^3 for the aggregate is based on OSKP 2022.

The price determination procedure is described in chapter 4.2. Tab. 33 - Tab. 34 show the cubic capacity of the material used to calculate the prices and the resulting costs. The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 33 Amounts of material required for the DuSO options

			DuSO 01, DuSO 02	DuSO 03
	Corridor excavation method	Aggregate - unit price according to OTSKP 2022 [CZK/m^3]	Cross-section [m^2]	Cross-section [m^2]
Vertical disposal	TBM mechanised mining method	344	41.29	38.48
	Conventional mining method		36.32	
Horizontal disposal	TBM mechanised mining method		38.48	
	Conventional mining method		36.32	

Tab. 34 Estimation of prices: VY 05.02

		DuSO 01, DuSO 02	DuSO 03
	Prevailing corridor excavation method	Component price [CZK thousand/m length of the construction entity]	Component price [CZK thousand/m length of the construction entity]
Vertical disposal	TBM mechanised mining method	14.2	13.2
	Conventional mining method	12.5	
Horizontal disposal	TBM mechanised mining method	13.2	
	Conventional mining method	12.5	

5.10 VY 06.01 Plug – Operational plug for horizontal disposal boreholes

5.10.1 Component details

Name	Plug – Operational plug for horizontal disposal boreholes
Description	A concrete structure placed at the mouth of the backfilled horizontal disposal boreholes; conical in shape and wedged into the rock in the form of a ring around the entire borehole
Location in the DGR	Horizontal disposal boreholes, confirmation laboratory
Applicability conditions	Clean excavation without significant disturbances or active water inflows (the exact criteria will be specified in the future) No materials must be introduced into the horizontal disposal boreholes (e.g. lining remnants, ground levelling, etc.). *The permitted amount of introduced materials will be specified in future*
Subvariants	01 Operational plug made of fibre shotcrete 02 Operational plug made of monolithic reinforced/fibre-reinforced concrete
Material	01 Concrete 02 Steel (reinforcement)
Subcomponents	01 Body of the plug (fibre shotcrete, monolithic reinforced /fibre-reinforced concrete) 02 Concrete blocks 03 Reinforcement - steel (bars, mesh) Note: the backfilling of the horizontal disposal boreholes (VY 01.01, VY 01.02)
Production/preparation technology	01 Production of concrete mixture at the concrete plant and its transport to the underground part of the DGR using cement mixer trucks 02 Preparation and production of the concrete blocks and their transport to the underground part of the DGR using special transport vehicles 03 Reinforcement and installation of the formwork

Installation/construction technology	01 Masonry using mortar mixtures and filling concrete 02 Installation of the plug via shotcrete spraying method using a handling device 03 Concreting of the monolithic plug

5.10.2 Component requirements

5.10.2.1 External requirements and specifications

According to the 580/2022 report (Dohnálková et al., 2022), the design parameters of the plug are based primarily on the needs of the DGR project design (Grünwald et al., 2018) and previous research conducted in connection with the international DOPAS project (Dvořáková et al., 2014).

The design parameters of the plug are as follows:

- Resistance to the backfill swelling pressure and hydrostatic pressure: 7 MPa.
- Compressive strength of the construction material of the plug: this value has not yet been determined.

The geometry of the plug in the case of the horizontal disposal of SNF WDPs will be based on the horizontal disposal borehole design parameter provided in the 134/2017 report (Grünwald et al., 2018):

- Diameter of the disposal borehole: 2,200 mm

Alternatively, a borehole diameter of 1,700 mm is being considered, i.e. the smallest diameter in terms of ensuring the thickness of the buffer of 350 mm (see VY 01.02).

5.10.2.2 Required safety and technical functions

The operational plug will have a mechanical function during the operation of the DGR, to which the construction approach will be required to correspond.

From the long-term point of view, the choice of the material used and its chemical compatibility with the other engineered barriers will be important since the plugs, unlike the other structural components, will remain in the DGR following its closure.

According to technical report 616/2022 (Večerník et al., 2022), low-pH concretes are being considered as the construction material for the DGR disposal horizon. The report describes the potential interaction between the various materials of the structural components, as well as the influence of bentonite as the engineered barrier backfill material and the influence of the rock environment and the groundwater (which will exert an influence on the overall chemical-geochemical development of the repository) and the influence of the mineralogical composition, physical and mechanical properties and microbial composition of the engineered barrier materials.

The undesirable development of microorganisms may occur at the interface of the component and the bentonite filling of the horizontal disposal borehole mainly due to the space provided at the interface of the materials. In addition, alkaline leachates from the concrete may lead to changes in the bentonite and, via influencing the swelling pressure and density of the bentonite, create additional living space for microorganisms (Večerník et al., 2022). However, the higher pH of the concrete will exert a net positive effect on the bentonite from the microbiological point of view in the sense of suppressing the microbial activity (for more details, see chapter 3.2 and Večerník et al., 2022). In the case of the use of low-pH concrete, the development of microbial activity can be expected earlier than with ordinary concrete.

5.10.3 Component design assumptions

The conceptual design is based on:

- the required dimensions as set out in the 580/2022 report (Dohnálková et al., 2022)
- the anticipated interactions as described in the 616/2022 report (Večerník et al., 2022)
- the requirements concerning the safety functions
- technical feasibility
- economic feasibility

In contrast to the requirements of the 580/2022 report (Dohnálková et al., 2022), the plug design has been optimised as a single-layer concrete structure.

5.10.4 Component description

At the time of the consideration of the DGR project design (Grünwald et al., 2018), although the detailed design of this component and the technology for its construction had not been developed in detail, it was considered that in the case of the horizontal disposal concept, the plug would be located 7.5 m from the mouth of the borehole; the plug, with a thickness of 2.5 m, is planned to be wedged into the rock in the form of a ring around the whole of the borehole.

The design of the geometry of the sealing plug will have to be verified via static calculations and designed with regard to the key dimensioning conditions, taking into account the stress conditions in the disposal horizon, the expected swelling pressures acting on the plug, the operational conditions during the filling of the horizontal disposal borehole, etc.

A detail of the operational plug for the horizontal disposal borehole concept is shown in Fig. 15.

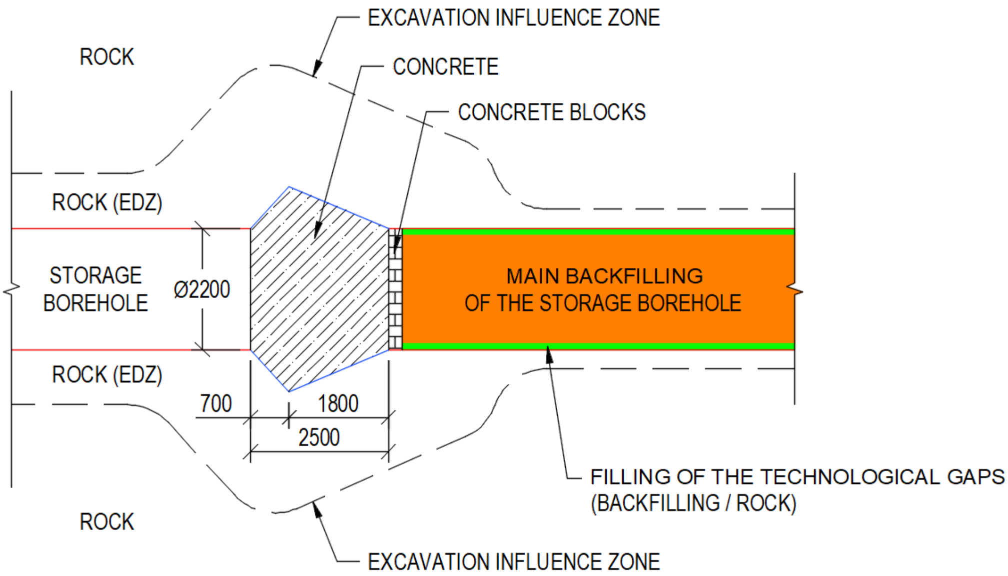

Fig. 15 Detail of the operational plug for the horizontal disposal borehole concept

A diagram of the operational plug for the horizontal disposal borehole concept is shown in Fig. 16.

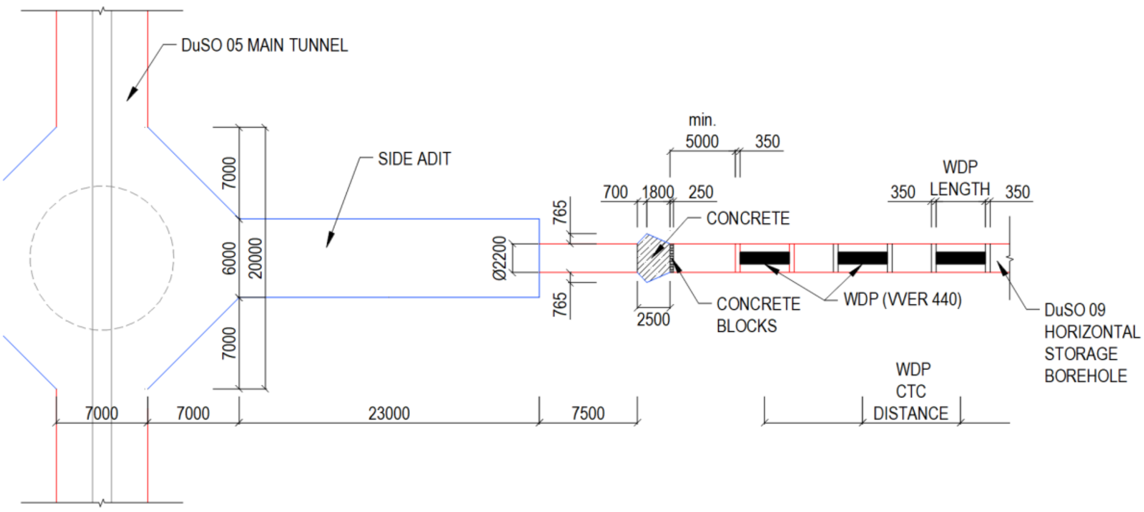

Fig. 16 Diagram of the operational plug for the horizontal disposal borehole concept

5.10.5 Locations of applicability in the DGR

In the case of the horizontal disposal option, the operational plug will serve to seal the disposal boreholes (DuSO 09) located in the disposal horizon.

5.10.6 Applicability conditions

From the viewpoint of the safety of the DGR, the component requires:

- Clean excavation without significant disturbances or active water inflows (the exact criteria will be specified in the future)
- No materials must be introduced into the horizontal disposal boreholes (e.g. lining remnants, ground levelling, etc.) that could negatively affect the safety of the DGR. *The permitted amount of introduced materials will be specified in future.*

5.10.7 Subvariants and the subcomponents thereof

The operational plug for the horizontal disposal boreholes will be made from concrete blocks, from which a sealing wall will be constructed, which will act to restrain the backfilling material during the construction of the plug itself; alternatively, the plug will be made from fibre reinforced shotcrete (01) or monolithic concrete (02).

5.10.7.1 01 Body of the plug

5.10.7.1.1 01 Operational plug made from fibre shotcrete

The basic properties and required parameters of shotcrete are described in (Hilar et al., 2008), mainly in connection with its use with the NRTM method. The composition, requirements and specifications of the concrete mixture must respect the data requirements specified in chapter 3.2.2.

Previously conducted research as part of the international DOPAS project considered the use of fibre shotcrete with a minimum compressive strength of 30 MPa, tensile strength of 3 MPa and hydraulic conductivity of 10^{-10} m/s, with a reduced pH for the construction of the plug; the aim was to limit the potential for damaging the bentonite via leaching from the concrete (Dvořáková et al., 2014). As considered by the international DOPAS project, glass fibres may be used as a form of dispersed reinforcement, the function of which would, primarily, be to reduce the number of cracks resulting from shrinkage and to enhance the strength characteristics.

5.10.7.1.2 02 Sealing plug made from monolithic reinforced concrete

The composition, requirements and specifications of the concrete mixture must respect the data requirements specified in chapter 3.2.1.1. The reinforcement of the monolithic plug will be proposed in the future.

5.10.7.2 02 Closure wall made from concrete blocks

A basic description of the concrete blocks from which the sealing wall (a subcomponent of the operational plug) will be constructed was presented in chapter 3.2.3. For the purposes of this report, it is assumed that the wall will be 0.25 m thick (a typical example of the wall thickness required for this purpose). The closure wall will fulfil the function of the lost formwork.

5.10.7.3 03 Reinforcing steel

Solid, mostly circular steel rods (smooth and ribbed) will be inserted into the concrete so as to increase its load-bearing capacity and reduce deformations (rods, meshing). The type and amount of the reinforcement required for the sealing plug will be specified in the future.

5.10.8 Production/preparation technology

5.10.8.1 01 Operational plug made from fibre shotcrete

The wet concrete mixture, which will be used in the construction of the sealing plug, will be produced at the concrete plant and transported to the underground part of the DGR using cement mixer trucks.

5.10.8.2 02 Sealing plug made from reinforced monolithic concrete

In a similar way to the sealing plug made of fibre shotcrete, the concrete mixture will also be produced in the concrete plant and transported to the underground part of the DGR using cement mixer trucks. Following the installation of reinforcement, the fresh concrete mixture will be poured into formwork in which it will be compacted.

5.10.8.3 03 Sealing wall made from concrete blocks

The concrete blocks that will be used in the construction of the plug will be made of vibration-compressed high-strength concrete as with industrially produced building components in construction plants and transported to the underground part of the DGR using special transport vehicles.

5.10.8.4 04 Reinforcing steel

Industrially processed concrete reinforcement steel (bars, meshing).

5.10.9 Installation/construction technology

Following the removal of any equipment that remains in the horizontal disposal boreholes, the construction of the lost formwork consisting of concrete blocks will commence in parallel with the backfilling of the boreholes with component VY 01.01 or VY 01.02, which is described in more detail in chapters 5.1 and 5.2, respectively. The adherence of the contact surfaces of the blocks will be ensured by a mortar mixture, which will allow for their mutual support. After stacking the concrete blocks, the wall will infilled with concrete.

Once the construction of the lost formwork has been completed, the construction will commence of the body of the plug itself, which will be made from fibre shotcrete or monolithic concrete.

The construction of plugs from fibre shotcrete via the wet application method will be preceded by the treatment of the surface, i.e. the removal of loose and poor-quality parts of the rock. The issue of diverting or sealing more significant water inflows will be addressed at a later stage. Concerning the spraying process, a technological procedure will have to be determined according to the specific conditions of the application of the shotcrete, which will determine, *inter alia*, the spraying procedure, the distance and direction of the nozzle, the temperature of the underlying surfaces of the spray and the treatment of the concrete.

The construction of the plug from monolithic concrete will also be preceded by surface treatment in the sense of removing any loose or poor-quality parts of the rock, after which, following reinforcement, a temporary auxiliary structure will be fitted so as to create a mould for the emplacement and compacting of the fresh concrete (formwork). The technological procedure for the concreting of the plug will have to be determined according to the specific conditions.

5.10.10 Estimation of unit prices

The unit price is based on the industry classification manual for 2022 (OTSKP, 2022). Going forward, the price will depend on the geometry and volume of the plug based on detailed knowledge of the engineering-geological conditions, the stress in the rock mass, the swelling pressures acting on the plug, the operating conditions during backfilling, etc. The calculation of the price for the construction of the operational plug were based on the prices listed in Tab. 35. The calculation of the costs for the construction of the two options for the operational plugs of the horizontal disposal boreholes is shown in Tab. 36 and Tab. 37. The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 35 Overview of the unit prices used to estimate the price for the operational plug

Item name	Unit price according to OTSKP 2022
01 Sealing plug made from shotcrete with a min. strength of SB 30, i.e. C 25/30	7,780 CZK/m^3
02 Sealing wall made from concrete blocks	11,500 CZK/m^3
03 Monolithic reinforced concrete with a min. compressive strength of class C 30/37	8,470 CZK/m^3
04 Reinforcing steel (bars, meshing)	42,400 CZK/tonne

Tab. 36 Estimated price of the shotcrete operational plug for a horizontal disposal borehole (DuSO 09) excavated using the mechanised method

Item name	Volume [m^3]	Unit price [CZK thousand/m^3]	Total price [CZK thousand]
Sealing plug made from shotcrete with a min. strength of SB 30, i.e. C 25/30	13.15	102	113
Sealing wall made from concrete blocks	0.95	11	

Tab. 37 Estimated price of the monolithic reinforced concrete operational plug for a horizontal disposal borehole (DuSO 09) excavated using the mechanised

Item name	Volume/weight [m^3] / [tonnes]	Unit price [CZK thousand/m^3] / [CZK thousand/tonne]	Total price [CZK thousand]
Sealing wall made from concrete blocks	0.95	11	162
Walls made from reinforced concrete up to C 30/37	13.15	111	
Reinforcement of walls with 10505, B500B steel (reinforcement density 90 kg per 1 m^3 of concrete)	1.18	50	

5.11 VY 06.02 Plug – Operational plug for the loading corridor

5.11.1 Component details

Name	Plug – Operational plug for the loading corridor
Description	A concrete structure placed at the mouth of the backfilled loading corridor; conical in shape and wedged into the rock in the form of a ring around the entire corridor
Location in the DGR	Loading corridor, confirmation laboratory
Applicability conditions	Clean excavation without significant disturbances or active water inflows (the exact criteria will be specified in the future) No materials must be introduced into the loading corridor (e.g. lining remnants, ground levelling, etc.). *The permitted amount of introduced materials will be specified in future.*
Subvariants	01 Operational plug made from fibre shotcrete 02 Operational plug made from monolithic reinforced/fibre-reinforced concrete
Material	01 Concrete 02 Steel (reinforcement)
Subcomponents	01 Body of the plug (fibre shotcrete, monolithic reinforced /fibre-reinforced concrete) 02 Concrete blocks 03 Reinforcement steel (bars, mesh) Note: the backfilling of the loading corridor (VY 02.01)
Production/preparation technology	01 Production from a wet concrete mixture at the concrete plant and its transport to the underground part of the DGR using cement mixer trucks 02 Preparation and production of the concrete blocks and their transport to the underground part of the DGR using special transport vehicles 03 Reinforcement and installation of the formwork

Installation/construction technology	01 Masonry using mortar mixtures and filling concrete 02 Installation of the plug via the wet shotcrete method using a handling device 03 Concreting of the monolithic plug

5.11.2 Component requirements

5.11.2.1 External requirements and specifications

According to the 580/2022 report (Dohnálková et al., 2022), the design parameters of the plug are based primarily on the needs of the DGR project design (Grünwald et al., 2018) and previous research conducted in connection with the international DOPAS project (Dvořáková et al., 2014).

The design parameters of the plug are as follows:

- Resistance to the backfill swelling pressure and hydrostatic pressure: 7 MPa.
- Compressive strength of the construction material of the plug: this value has not yet been determined.

The geometry of the plug in the case of the vertical disposal of SNF WDPs will be based on the following design parameters for the loading corridor provided in the 580/2022 report (Dohnálková et al., 2022):

	Conventional excavation	TBM excavation
Corridor height	6,700 mm	7,250 mm
Corridor width	4,000 mm	7,250 mm

5.11.2.2 Required safety and technical functions

The required safety and technical functions are identical to those of component 06.01 (see chapter 5.10.2.2) with the following difference: the undesirable development of microorganisms may occur at the interface of the component and in the bentonite backfilling of the loading corridor.

5.11.3 Component design assumptions

The conceptual design is based on:

- the required dimensions as set out in the 580/2022 report (Dohnálková et al., 2022)
- the anticipated interactions as described in the 616/2022 report (Večerník et al., 2022)
- the requirements concerning the safety functions
- technical feasibility
- economic feasibility

In contrast to the requirements of the 580/2022 report (Dohnálková et al., 2022), the plug design has been optimised as a single-layer concrete structure.

5.11.4 Component description

At the time of the consideration of the DGR project design (Grünwald et al., 2018), although the detailed design of this component and the technology for its construction had not been developed in detail, it was considered that in the case of the vertical disposal concept, the plug would be located 7.5 m from the mouth of the corridor; the plug, with a thickness of 2.5 m, is planned to be wedged into the rock in the form of a ring around the whole of the corridor.

The design of the geometry of the sealing plug will have to be verified via static calculations and designed with regard to the key dimensioning conditions, taking into account the stress conditions in the disposal horizon, the expected swelling pressures acting on the plug, the operational conditions during the filling of the loading corridor, etc.

A detail of the operational plug for the loading corridor is shown in Fig. 17.

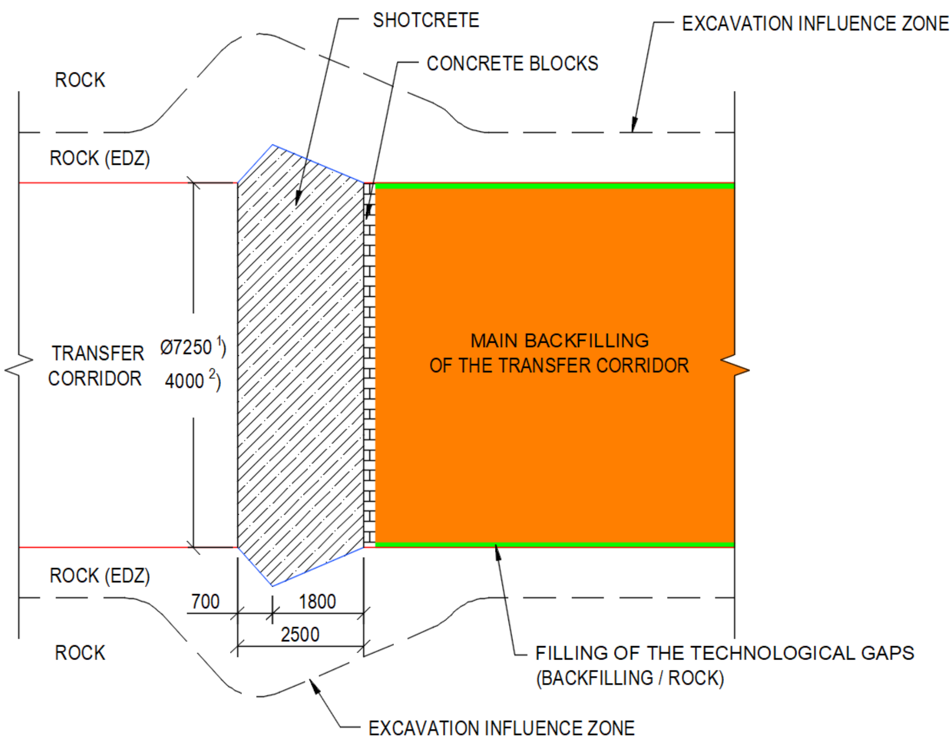

Fig. 17 Detail of the operational plug for the loading corridor
Notes: [1]) Diameter of the loading corridor excavated using the TBM method, [2]) Width of the loading corridor excavated using the conventional method

Diagrams of the operational plug for the loading corridor excavated using the TBM method and the conventional method are shown in Fig. 18 and Fig. 19.

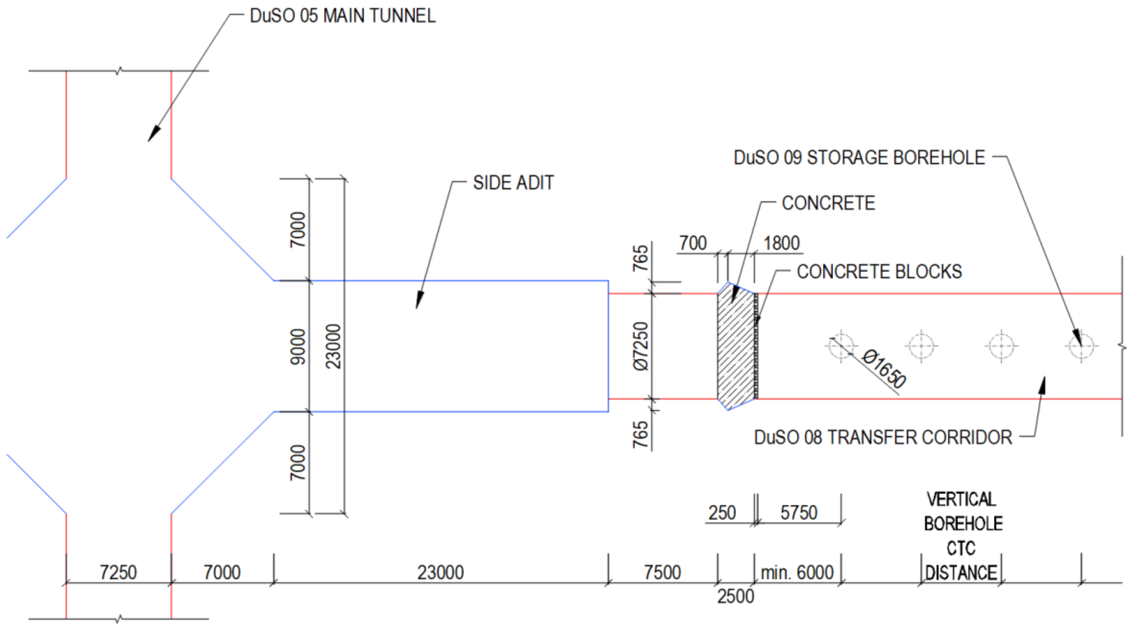

Fig. 18 Diagram of the operational plug for the loading corridor excavated using the TBM method

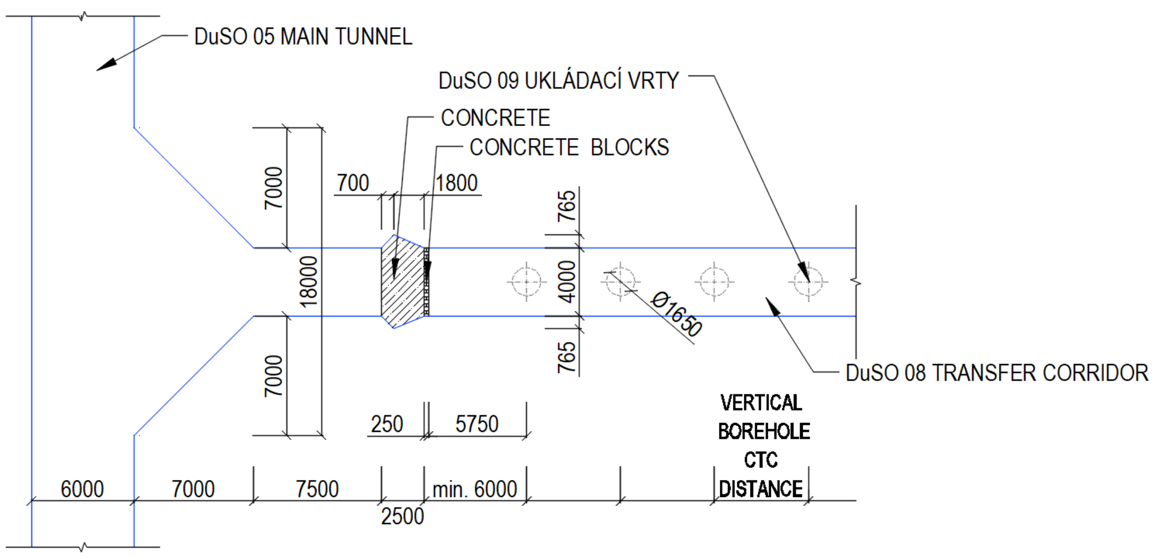

Fig. 19 Diagram of the operational plug for the loading corridor excavated using the conventional method

5.11.5 Locations of applicability in the DGR

In the case of the vertical disposal option, the operational plug will serve to seal the loading corridor (DuSO 08) located in the disposal horizon.

5.11.6 Applicability conditions

The applicability conditions are identical to those of component VY 06.01 (see chapter 5.10.6), with the difference that no introduced materials (e.g. lining remnants, ground levelling, etc.) should remain in the loading corridor.

5.11.7 Subvariants and the subcomponents thereof

The subvariants and their subcomponents are identical to those of the VY 06.01 component (see chapter 5.10.7), with the difference that the operational plug serves to seal the loading corridor.

5.11.8 Production/preparation technology

The production and preparation technology is identical to that of the VY 06.01 component. See chapter 5.10.8.

5.11.9 Installation/construction technology

The construction technology of the operational plug is the same as for the VY 06.01 component (see chapter 5.10.9), with the difference that the construction of the sealing wall will commence following the removal of the loading corridor equipment in parallel with the backfilling of the loading corridor.

5.11.10 Estimation of unit prices

The unit price is based on the industry classification manual for 2022 (OTSKP, 2022). Going forward, the price will depend on the geometry and volume of the plug based on detailed knowledge of the engineering-geological conditions, the stress in the rock mass, the swelling pressures acting on the plug, the operating conditions during backfilling, etc. The calculation of the price for the construction of the operational plug were based on the prices listed in Tab. 35. The calculation of the costs for the construction of the two options for the operational plugs, the type of which will depend on the choice of the loading corridor excavation method, is shown in Tab. 38 to Tab. 41. The procedure for the calculation of the price estimation is described in Annex No. 1

Tab. 38 Estimated price of the shotcrete operational plug for the loading corridor (DuSO 08) excavated using the mechanised method

Item name	Volume [m^3]	Item price [CZK thousand/m^3]	Total price [CZK thousand]
Operational plug made from shotcrete with a min. strength of SB 30 (C 25/30)	125.09	973	1,092
Sealing wall made from concrete blocks	10.32	119	

Tab. 39 Estimated price of the operational plug for the loading corridor made from monolithic reinforced concrete (DuSO 08) excavated using the mechanised method

Item name	Volume/weight [m^3] / [tonnes]	Item price [CZK thousand/m^3] / [CZK thousand/tonne]	Total price [CZK thousand]
Sealing wall made from concrete blocks	10.32	119	1,656
Walls made from reinforced concrete up to C 30/37	125.09	1,060	
Reinforcement of walls with10505, B500B steel (reinforcement density 90 kg per 1 m^3 of concrete)	11.26	477	

Tab. 40 Estimated price of the shotcrete operational plug for the loading corridor (DuSO 08) excavated using the mechanised method

Item name	Volume [m^3]	Item price [CZK thousand/m^3]	Total price [CZK thousand]
Operational plug made from shotcrete with a min. strength of SB 30 (C 25/30)	82.01	638	711
Sealing wall made from concrete blocks	6.31	73	

Tab. 41 Estimated price of the operational plug for the loading corridor made from monolithic reinforced concrete (DuSO 08) excavated using the mechanised method

Item name	Volume/weight [m^3] / [tonnes]	Item price [CZK thousand/m^3] / [CZK thousand/tonne]	Total price [CZK thousand]
Sealing wall made from concrete blocks	0.95	11	852
Walls made from reinforced concrete up to C 30/37	13.15	111	
Reinforcement of walls with10505, B500B steel (reinforcement density 90 kg per 1 m^3 of concrete)	1.18	50	

5.12 VY 06.03 Plug – Operational plug for the RAW disposal chambers

5.12.1 Component details

Name	Plug – Operational plug for the RAW disposal chambers
Description	A concrete structure placed at the end of the corridor leading to the backfilled RAW disposal chamber; conical in shape and wedged into the rock in the form of a ring around the entire corridor
Location in the DGR	RAW disposal chambers
Applicability conditions	Clean excavation without significant disturbances or active water inflows (the exact criteria will be specified in the future) No materials must be introduced into the area of the plug of the RAW disposal chambers (e.g. lining remnants, ground levelling, etc.). *The permitted amount of introduced materials will be specified in future.*
Subvariants	01 Operational plug made of fibre shotcrete 02 Operational plug made of monolithic reinforced /fibre-reinforced concrete
Material	01 Concrete 02 Steel (reinforcement)
Subcomponents	01 Body of the plug (fibre shotcrete, monolithic reinforced /fibre-reinforced concrete) 02 Concrete blocks 03 Reinforcement steel (bars, mesh) Note: the backfilling of the RAW disposal chambers (VY 03.01, VY 03.02)
Production/preparation technology	01 Production from a wet concrete mixture at the concrete plant and its transport to the underground part of the DGR using cement mixer trucks 02 Preparation and production of the concrete blocks and their transport to the underground part of the DGR using special transport vehicles 03 Reinforcement and installation of the formwork

Installation/construction technology	01 Masonry using mortar mixtures and filling concrete 02 Installation of the plug via the wet concrete spraying method using a handling device 03 Concreting of the monolithic plug

5.12.2 Component requirements

5.12.2.1 External requirements and specifications

The requirements are identical to those of the VY 06.01 component (see chapter 5.10.2), with the difference that the geometry of the plug is based on the design parameters of the opening of the corridor into the RAW chamber according to the DGR project design (Grünwald et al., 2018):

- Corridor height: 5,400 mm.
- Corridor width: 5,600 mm.

5.12.2.2 Required safety and technical functions

Identical to component VY 06.01. See chapter 5.10.2.2.

5.12.3 Component design assumptions

Identical to component VY 06.01. See chapter 5.10.3.

5.12.4 Component description

At the time of the development of the DGR project design (Grünwald et al., 2018), although the detailed design of this component and the technology for its construction had not been developed in detail, it was considered that the plug would be placed at the end of the corridor opening into the RAW chamber; the plug, with a thickness 1.5 m, will be wedged into the rock in the form of a ring around the whole of the corridor.

The design of the geometry of the RAW chamber operational plug will have to be verified via static calculations and designed with regard to the key dimensioning conditions, taking into account the stress conditions in the disposal horizon, the expected swelling pressures acting on the plug, the operational conditions during the filling of the chambers, etc.

A diagram of the operational plug for the RAW chambers is shown in Fig. 20.

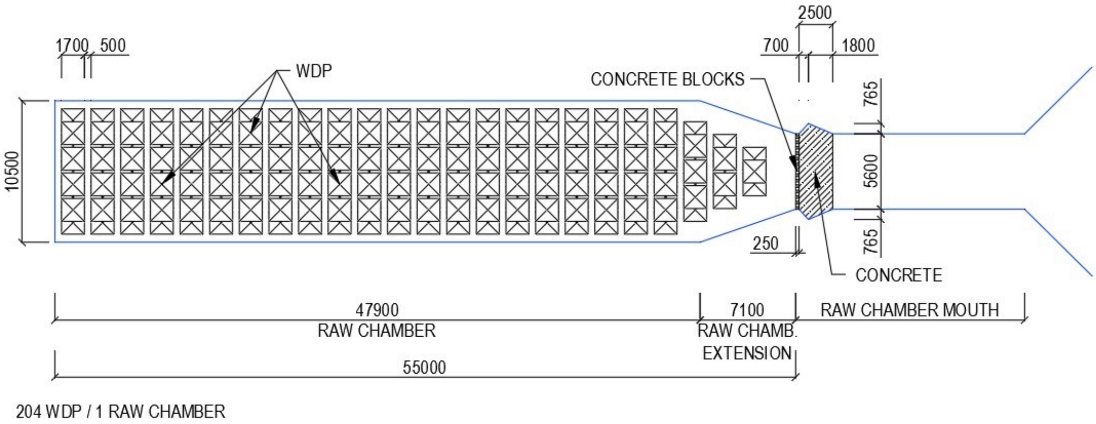

Fig. 20 Diagram of the operational plug for the RAW chambers

5.12.5 Locations of applicability in the DGR

The operational plug will serve to seal the RAW disposal chambers (DuSO 11), which, according to the division of the closure of the DGR into sections according to depth (580/2022 report (Dohnálková et al., 2022)), is located in the so-called middle horizon.

5.12.6 Applicability conditions

From the point of view of the safety of the DGR, the component requires:

- Clean excavation without significant disturbances or active water inflows (the exact criteria will be specified in the future)
- No materials must be introduced into the area of the plug of the RAW disposal chambers (e.g. lining remnants, ground levelling, etc.), which could negatively affect the safety of the DGR. *The permitted amount of introduced materials will be specified in future.*

5.12.7 Subvariants and the subcomponents thereof

Identical to those of component VY 06.01. See chapter 5.10.7.

5.12.8 Production/preparation technology

Identical to those of component VY 06.01. See chapter 5.10.8.

5.12.9 Installation/construction technology

Identical to those of component VY 06.01. See chapter 5.10.9.

5.12.10 Estimation of unit prices

The unit price is based on the industry classification manual for 2022 (OTSKP, 2022). Going forward, the price will depend on the geometry and volume of the plug based on detailed knowledge of the engineering-geological conditions, the stress in the rock mass, the swelling pressures acting on the plug, the operating conditions during backfilling, etc. The calculation of the price for the construction of the operational plug were based on the prices listed in Tab. 35. The calculation of the costs of the construction of the two variants of the RAW chamber operational plugs is provided in Tab. 38 to Tab. 41. The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 42 Estimated price of the RAW chamber operational plug made from fibre shotcrete (DuSO 11)

Item name	Volume [m^3]	Item price [CZK thousand/m^3]	Total price [CZK thousand]
Operational plug made from shotcrete with a min. strength of SB 30 (C 25/30)	85.11	662	739
Sealing wall made from concrete blocks	6.69	77	

Tab. 43 Estimated price of the RAW chamber operational plug made from monolithic reinforced concrete (DuSO 11)

Item name	Volume/weight [m^3] / [tonnes]	Item price [CZK thousand/m^3] / [CZK thousand/tonne]	Total price [CZK thousand]
Sealing wall made from concrete blocks	6.69	77	1,123
Walls made from reinforced concrete up to C 30/37	85.11	721	
Reinforcement of walls with10505, B500B steel (reinforcement density 90 kg per 1 m^3 of concrete)	7.66	325	

5.13 VY 06.04 Plug – Operational plug for the disposal horizon

5.13.1 Component details

Name	Plug – Operational plug for the disposal horizon
Description	A concrete structure placed in predetermined locations of the backfilled corridors (caverns); conical in shape, wedged into the rock in the form of a ring around the entire corridor.
Location in the DGR	Main corridors, technical facilities of the underground part of the DGR (corridors, caverns)
Applicability conditions	• Clean excavation without significant disturbances or active water inflows (the exact criteria will be specified in the future) • No materials must be introduced into the main corridor (e.g. lining remnants, ground levelling, etc.). *The permitted amount of introduced materials will be specified in future.*
Subvariants	01 Operational plug made of fibre shotcrete 02 Operational plug made of monolithic reinforced /fibre-reinforced concrete
Material	01 Concrete 02 Steel (reinforcement)
Subcomponents	01 Body of the plug (fibre shotcrete, monolithic reinforced /fibre-reinforced concrete) 02 Concrete blocks 03 Reinforcement steel (bars, mesh) Note: the backfilling of the space in the disposal horizon (VY 04.01)
Production/preparation technology	01 Production from a wet concrete mixture at the concrete plant and its transport to the underground part of the DGR using cement mixer trucks 02 Preparation and production of the concrete blocks and their transport to the underground part of the DGR using special transport vehicles 03 Reinforcement and installation of the formwork

Installation/construction technology	01 Masonry using mortar mixtures and filling concrete 02 Installation of the plug via the wet concrete spraying method using a handling device 03 Concreting of the monolithic plug

5.13.2 Component requirements

5.13.2.1 External requirements and specifications

The requirements are identical to those of the VY 06.01 component (see chapter 5.10.2.1). The geometry of the plug in the disposal horizon is based on the design parameters of the main corridors and the technical background of the underground part of the DGR (corridors, caverns) according to the DGR project design (Grünwald et al., 2018).

5.13.2.2 Required safety and technical functions

Identical to component VY 06.01. See chapter 5.10.2.2

5.13.3 Component design assumptions

Identical to component VY 06.01. See chapter 5.10.3.

5.13.4 Component description

At the time of the development of the DGR project design (Grünwald et al., 2018), although the detailed structural design of this component and the construction technology and location had not been considered in detail, it was anticipated that the plug would be wedged into the rock in the form of a ring around the whole of the corridor.

Therefore, it will be necessary to verify the design of the considered geometry of the sealing plug via static calculations and to design the plug taking into account the key dimensioning conditions with the consideration of the stress conditions in the disposal horizon, the expected swelling pressures acting on the plug, the operational conditions during the filling of the corridors and caverns in line with the technical layout of the underground part of the DGR etc.

A diagram of the considered geometry of the plug for the mechanised and conventionally excavated main corridor with regard to its greatest width, regardless of the disposal method, is shown in Fig. 21.

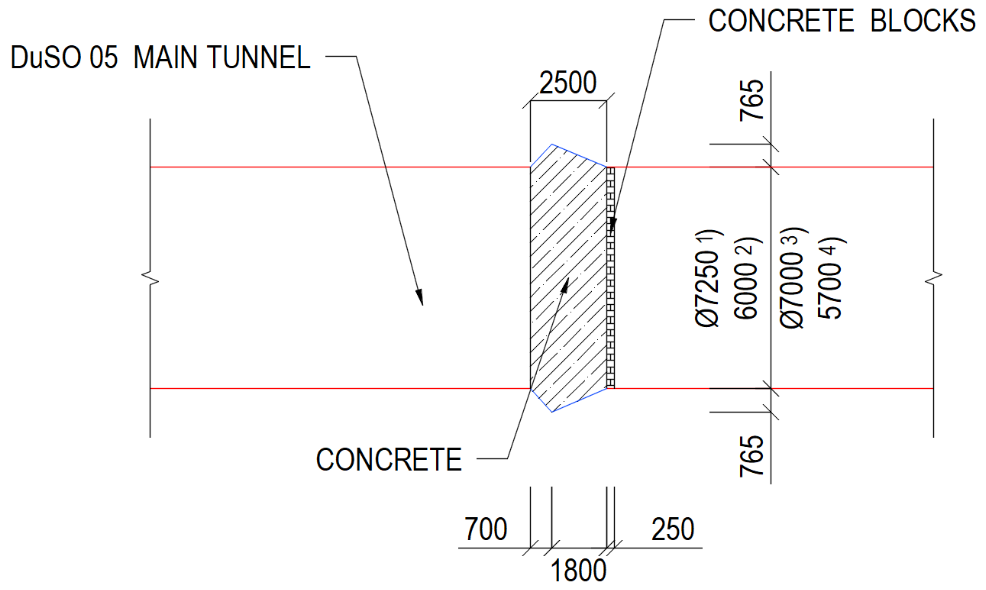

Fig. 21 Diagram of the operational plug for the main corridor in the disposal horizon
Notes: 1) Diameter of the main corridor excavated via the TBM method – vertical disposal, 2) Width of the main corridor excavated via the conventional method – vertical disposal, 3) Diameter of the main corridor excavated via the TBM method – horizontal disposal, 4) Width of the main corridor excavated via the conventional method – horizontal disposal

5.13.5 Locations of applicability in the DGR

The operational plug in the disposal horizon serves to seal the main corridors and the technical facilities of the underground part of the DGR (corridors and caverns).

5.13.6 Applicability conditions

From the point of view of the safety of the DGR, the component requires:

- Clean excavation without significant disturbances or active water inflows (the exact criteria will be specified in the future)
- No materials must be introduced into the area of the main corridor (e.g. lining remnants, ground levelling, etc.). *The permitted amount of introduced materials will be specified in future.*

5.13.7 Subvariants and the subcomponents thereof

Identical to those of component VY 06.01. See chapter 5.10.7.

5.13.8 Production/preparation technology

Identical to those of component VY 06.01. See chapter 5.10.8.

5.13.9 Installation/construction technology

Identical to those of component VY 06.01. See chapter 5.10.9.

5.13.10 Estimation of unit prices

The unit price is based on the industry classification manual for 2022 (OTSKP, 2022). Going forward, the price will depend on the geometry and volume of the plug based on detailed knowledge of the engineering-geological conditions, the stress in the rock mass, the swelling pressures acting on the plug, the operating conditions during backfilling, etc. The calculation of the price for the construction of the operational plug were based on the prices listed in Tab. 35. The calculation of the costs of the construction of the two variants of the operational plug depending on the disposal method and excavation of the main corridor is provided in Tab. 44 to Tab. 51. The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 44 Estimated price of the operational plug for the main corridor made from fibre shotcrete (DuSO 05) excavated using the mechanised method - vertical disposal

Item name	Volume [m^3]	Item price [CZK thousand/m^3]	Total price [CZK thousand]
Operational plug made from shotcrete with a min. strength of SB 30 (C 25/30)	125.09	973	1,092
Sealing wall made from concrete blocks	10.32	119	

Tab. 45 Estimated price of the operational plug for the main corridor made from monolithic reinforced concrete (DuSO 05) excavated using the mechanised method - vertical disposal

Item name	Volume/weight [m^3] / [tonnes]	Item price [CZK thousand/m^3] / [CZK thousand/tonne]	Total price [CZK thousand]
Sealing wall made from concrete blocks	10.32	119	1,656
Walls made from reinforced concrete up to C 30/37	125.09	1,060	
Reinforcement of walls with10505, B500B steel (reinforcement density 90 kg per 1 m^3 of concrete)	11.26	477	

Tab. 46 Estimated price of the operational plug for the main corridor made from fibre shotcrete (DuSO 05) excavated using the conventional method - vertical disposal

Item name	Volume [m^3]	Item price [CZK thousand/m^3]	Total price [CZK thousand]
Operational plug made from shotcrete with a min. strength of SB 30 (C 25/30)	92.76	722	806
Sealing wall made from concrete blocks	7.31	84	

Tab. 47 Estimated price of the operational plug for the main corridor made from monolithic reinforced concrete (DuSO 05) excavated using the conventional method - vertical disposal

Item name	Volume/weight [m^3] / [tonnes]	Item price [CZK thousand/m^3] / [CZK thousand/tonne]	Total price [CZK thousand]
Sealing wall made from concrete blocks	7.31	84	1,224
Walls made from reinforced concrete up to C 30/37	92.76	786	
Reinforcement of walls with10505, B500B steel (reinforcement density 90 kg per 1 m^3 of concrete)	8.35	354	

Tab. 48 Estimated price of the operational plug for the main corridor made from fibre shotcrete (DuSO 05) excavated using the mechanised method - horizontal disposal

Item name	Volume [m^3]	Item price [CZK thousand/m^3]	Total price [CZK thousand]
Operational plug made from shotcrete with a min. strength of SB 30 (C 25/30)	117.31	913	1,024
Sealing wall made from concrete blocks	9.62	111	

Tab. 49 Estimated price of the operational plug for the main corridor made from monolithic reinforced concrete (DuSO 05) excavated using the mechanised method - horizontal disposal

Item name	Volume/weight [m^3] / [tonnes]	Item price [CZK thousand/m^3] / [CZK thousand/tonne]	Total price [CZK thousand]
Sealing wall made from concrete blocks	9.62	111	1,553
Walls made from reinforced concrete up to C 30/37	117.31	994	
Reinforcement of walls with10505, B500B steel (reinforcement density 90 kg per 1 m^3 of concrete)	10.56	448	

Tab. 50 Estimated price of the operational plug for the main corridor made from fibre shotcrete (DuSO 05) excavated using the conventional method - horizontal disposal

Item name	Volume [m^3]	Item price [CZK thousand/m^3]	Total price [CZK thousand]
Operational plug made from shotcrete with a min. strength of SB 30 (C 25/30)	92.67	721	805
Sealing wall made from concrete blocks	7.31	84	

Tab. 51 Estimated price of the operational plug for the main corridor made from monolithic reinforced concrete (DuSO 05) excavated using the conventional method - horizontal disposal

Item name	Volume/weight [m^3] / [tonnes]	Item price [CZK thousand/m^3] / [CZK thousand/tonne]	Total price [CZK thousand]
Sealing wall made from concrete blocks	7.31	84	1,223
Walls made from reinforced concrete up to C 30/37	92.67	785	
Reinforcement of walls with10505, B500B steel (reinforcement density 90 kg per 1 m^3 of concrete)	8.34	354	

5.14 VY 06.05 Plug - Pressure and sealing plug (separation of water inflows/fracture zones)

5.14.1 Component details

Name	Plug - Pressure and sealing plug (separation of water inflows/fracture zones)
Description	A concrete structure placed the tunnel/main corridor at the sites of tectonic fractures; conical in shape and wedged into the rock in the form of a ring around the entire tunnel/corridor.
Location in the DGR	Unloading and loading tunnel, main corridor
Applicability conditions	No materials must be introduced into the tunnel/main corridor (e.g. lining remnants, ground levelling, etc.). *The permitted amount of introduced materials will be specified in future.*
Subvariants	01 Pressure and sealing plug made of fibre shotcrete 02 Pressure and sealing plug made of monolithic reinforced /fibre-reinforced concrete
Material	01 Concrete 02 Steel (reinforcement)
Subcomponent	01 Body of the plug (fibre shotcrete, monolithic reinforced /fibre-reinforced concrete) 02 Concrete blocks 03 Reinforcement steel (bars, mesh) Note: The backfilling of spaces in the disposal horizon (VY 04.01)/filling of spaces above the disposal horizon - medium depth (VY 05.01)
Production/preparation technology	01 Production from a wet concrete mixture at the concrete plant and its transport to the underground part of the DGR using cement mixer trucks 02 Preparation and production of the concrete blocks and their transport to the underground part of the DGR using special transport vehicles 03 Reinforcement and installation of the formwork

Installation/construction technology	01 Masonry using mortar mixtures and filling concrete 02 Installation of the plug via the wet concrete spraying method using a handling device 03 Concreting of the monolithic plug

5.14.2 Component requirements

5.14.2.1 External requirements and specifications

The requirements are identical to those of the VY 06.01 component (see chapter 5.10.2.1), with the difference that the geometry of the plug will primarily be based on the needs of the DGR project design as set out in the 134/2017 report (Grünwald et al., 2018) and the design parameters of selected mine constructions according to the 580/2022 report (Dohnálková et al., 2022).

5.14.2.2 Required safety and technical functions

The required safety and technical functions of the pressure and sealing plug over the long term are identical to those of the VY 06.01 component (see chapter 5.10.2.2).

It is anticipated that the plugs will be placed in pre-determined locations on both sides of the aquifer section (tectonic disturbances) in such a way as to separate and seal this section from the other parts of the underground area of the DGR.

5.14.3 Component design assumptions

The conceptual design is based on:

- the required dimensions as set out in the 580/2022 report (Dohnálková et al., 2022)
- the anticipated interactions as described in the 616/2022 report (Večerník et al., 2022)
- the requirements concerning the safety functions
- technical feasibility
- economic feasibility

5.14.4 Component description

At the time of the development of the DGR project design (Grünwald et al., 2018), although the detailed design of this component and the technology for its construction had not been developed in detail, in line with previously conducted research as part of the international DOPAS project (Dvořáková et al., 2014) it will be a multi-layer construction consisting of external concrete parts in the shape of a cone, which will be wedged into the rock in the form of a ring around the whole of the tunnel/main corridor, and an internal sealing element made of a bentonite material located in the aquifer section (tectonic disturbances).

The design of the geometry of the pressure and sealing plug will have to be verified via static calculations and designed with regard to the key dimensioning conditions, taking into account the stress conditions, the expected swelling pressures acting on the plug, the operational conditions during the backfilling of the tunnel/main corridor, etc.

A diagram of the pressure and sealing plug of the main corridor excavated via the TBM method for the vertical disposal option (its use in the operational phase of the DGR remains open to debate) is shown in Fig. 22.

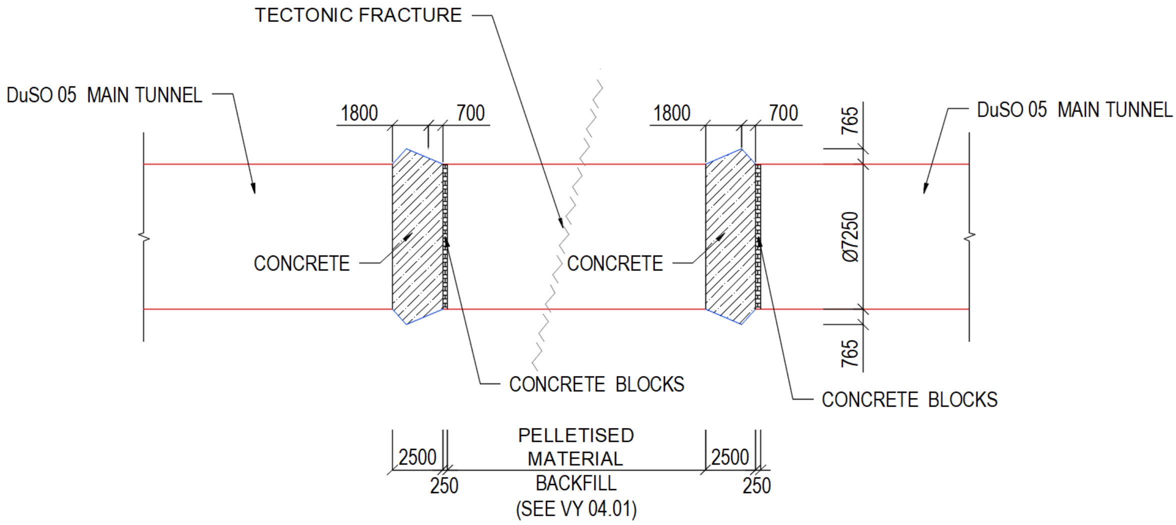

Fig. 22 Diagram of the pressure and sealing plug of the main corridor excavated via the TBM method

5.14.5 Locations of applicability in the DGR

Bearing in mind that for both the mechanised and conventional mining methods, the choice of which depends on the geological conditions (inflows, tectonic disturbances), additional measures or their combinations may have to be applied so as to enhance safety during the construction and operational phases of the DGR, the use of a pressure and sealing plug to separate places with water inflows/tectonic disturbances has not yet been confirmed.

5.14.6 Applicability conditions

From the point of view of the safety of the DGR, the component requires:

- No materials must be introduced into the area of the plug (e.g. lining remnants, ground levelling, etc.), which could negatively affect the safety of the DGR. *The permitted amount of introduced materials will be specified in future.*

5.14.7 Subvariants and the subcomponents thereof

Identical to those of component VY 06.01. See chapter 5.10.7.

5.14.8 Production/preparation technology

Identical to those of component VY 06.01. See chapter 5.10.8.

5.14.9 Installation/construction technology

The construction of two plugs, one on either side of the aquifer section (tectonic disturbances) is the same as that of component VY 06.01 (see chapter 5.10.9), with the difference that the construction of the plug will be coordinated with the bentonite material backfilling of both the connecting sections of the underground parts of the DGR and the internal sealing element, as described in more detail with concern to component VY 02.01.

5.14.10 Estimation of unit prices

The unit price is based on the industry classification manual for 2022 (OTSKP, 2022). Going forward, the price will depend on the geometry and volume of the plug based on detailed knowledge of the engineering-geological conditions, the stress in the rock mass, the swelling pressures acting on the plug, the operating conditions during backfilling, etc. The calculation of the price for the construction of the operational plug were based on the prices listed in Tab. 35. The calculation of the costs for the construction of both the operational plug variants, i.e. depending on the disposal method and the excavation method used for the main corridor, is shown in Tab. 44 to Tab. 51. The estimation of the prices for the backfilling of the main corridor is provided in Tab. 26. The total price of the plug, therefore, corresponds to the price of two operational plugs (VY 06.04) and the backfilling of the space between the plugs (VY 04.01), as summarised Tab. 52. The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 52 Estimation of the price of the pressure and sealing plug for the separation of inflow/disturbed area

Disposal method	Corridor excavation method	Operational plug of the main corridor made from fibre shotcrete	Operational plug of the main corridor made from monolithic reinforced concrete	Backfilling of the spaces in the disposal horizon
		Component price [CZK thousand]	Component price [CZK thousand]	Component price [CZK thousand/m length of the construction entity]
Vertical disposal	Mechanised TBM excavation method	1,092	1,656	468
	Conventional excavation method	806	1,224	332
Horizontal disposal	Mechanised TBM excavation method	1,023	1,552	436
	Conventional excavation method	805	1,223	332

5.15 VY 06.06 Plug – DGR closure plugs (inclined main tunnels, intake shaft)

5.15.1 Component details

Name	Plug – DGR closure plugs (inclined main tunnels, intake shaft)
Description	Reinforced concrete structure located at the mouth of the backfilled inclined main tunnels/backfilled intake shaft and dimensioned for the expected load
Location in the DGR	Inclined main tunnels, intake shaft
Applicability conditions	Removal of the equipment in the inclined main tunnels and the intake shaft.
Subvariants	01 Portal closure plug for the inclined main tunnels 02 Closure plug for the intake shaft
Material	01 Concrete 02 Reinforcement (steel)
Subcomponents	01 Concrete blocks 02 Monolithic reinforced concrete with a min. compressive strength class of C 30/37 with a degree of environmental impact of XF4 03 Reinforcing steel (bars, meshing) Note: The backfilling of the spaces in the disposal horizon (VY 04.01)/backfilling of the spaces above the disposal horizon – subsurface section (VY 05.01)
Production/preparation technology	01 Production of concrete at the concrete plant and its transport to the mouth of the main mine working of the DGR using cement mixer trucks 02 Preparation and production of the concrete blocks and their transport to the mouths of both tunnels using special transport vehicles 03 Reinforcement and installation of the formwork
Installation/construction technology	01 Masonry using mortar mixtures and filling concrete 02 Binding of the concrete reinforcement (bars, meshing) 03 Installation of a temporary auxiliary structure so as to create a mould for the placement and compaction of the fresh concrete 04 Concreting of the DGR sealing plugs

5.15.2 Component requirements

5.15.2.1 External requirements and specifications

The design parameters of the DGR closure plugs are based primarily on the needs of the DGR project design according to the 134/2017 report (Grünwald et al., 2018) and Czech Mining Authority Decree No. 52/1997 Coll., which sets out requirements for ensuring health and safety protection at work and operational safety during the closure of main mine workings, as amended. In addition, the surface plugs, according to the 575/2022 report (Kumpulainen et al., 2022) must also prevent the inadvertent entry of persons into the repository.

The geometries of the inclined main tunnel and intake shaft closure plugs both in the disposal horizon and on the surface will be based on the dimensions of the transverse profiles of the two tunnels according to Tab. 2 and annexes to the DGR project design (Grünwald et al., 2018).

The smallest dimension of the intake shaft plug (D_{min}) in metres will be determined according to paragraph 1 of Annex No. 3 of Czech Mining Authority Decree No. 52/1997 Coll. from relationship (1):

$$D_{min} = 1{,}5 \cdot (d + 2 \cdot t) \quad (1)$$

where

d is the largest clear dimension of the pit [m]. According to the annexes to the DGR project design (Grünwald et al., 2018) d = 7.0 m.

t - is the thickness of the lining of the shaft (m). According to the annexes to the DGR project design (Grünwald et al., 2018) t = 0.45 m.

After substituting the relevant values into formula (1), the smallest dimension of the shaft plug will be 10.5 m. From the point of view of its geometry, the smallest dimension concerns the diameter.

5.15.2.2 Required safety and technical functions

The plug will have a primarily mechanical function. It will prevent the intentional or unintentional intrusion of persons into the disposal area following its closure.

5.15.3 Component design assumptions

The conceptual design is based on:

- the design parameters as set out in the 134/2017 report (Grünwald et al., 2018).
- the anticipated interactions as described in the 616/2022 report (Večerník et al., 2022)
- the requirements concerning the safety functions
- technical feasibility
- economic feasibility

5.15.4 Component description

At the time of the development of the DGR project design (Grünwald et al., 2018), although the detailed design of these components and their construction technology had not been determined, the closure of main mine workings is currently governed by Czech Mining Authority Decree No. 52/1997 Coll.

According to section 2a) of the 52/1997 Coll. Decree, the intake shaft plug refers to a reinforced concrete slab placed over the mouth of the shaft and dimensioned according to the expected load.

The description of the closure plug for the inclined main tunnels is identical to that of component VY 06.04 (see chapter 5.13.4), with the difference that the design of the intake shaft plug has not yet been determined. With regard to the expected pressure of the backfill material, it can be concluded that the shaft closure plug will be made from steel-reinforced monolithic concrete.

A diagram of the intake shaft closure plug, according to Czech Mining Authority Decree No. 52/1997, is shown in Fig. 23.

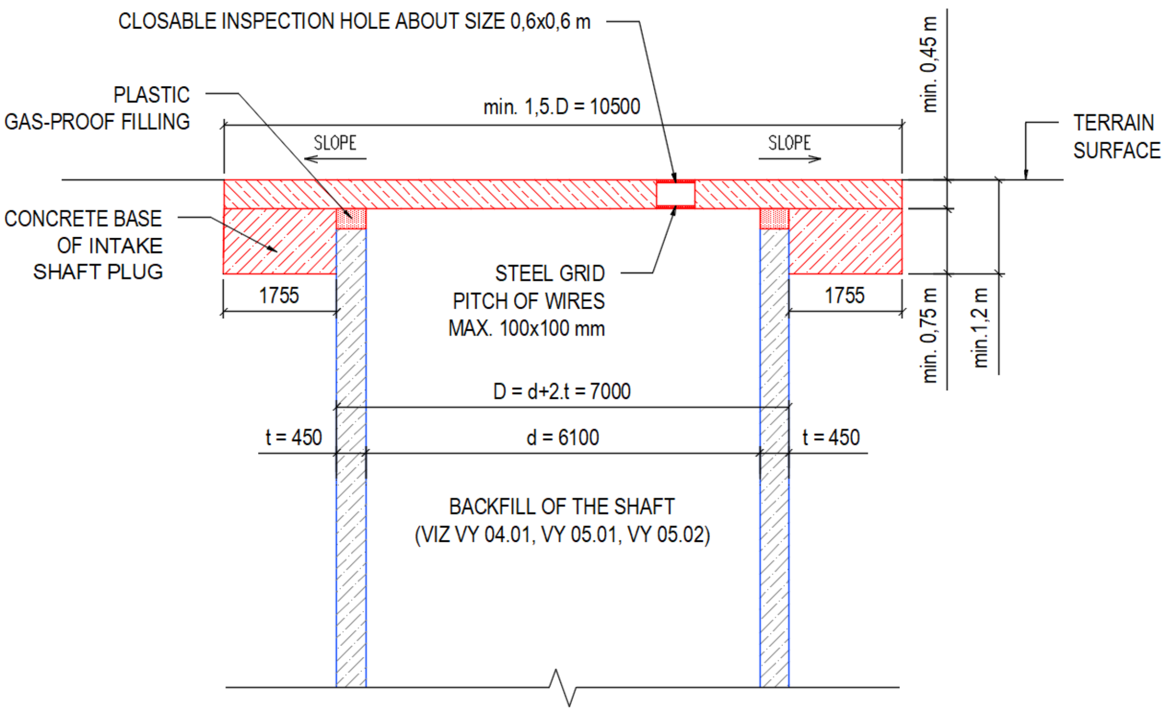

Fig. 23 Diagram of the intake shaft plug

It is of note that the current relevant decree sets out requirements concerning health and safety protection at work and operational safety during the closure of main mine workings with respect to both mining activities and the extraction of minerals. However, the method and principles set out in the decree may not meet the requirements with respect to long-term safety following the closure of the DGR. The requirements for the safety function of the DGR have not yet been defined in detail.

5.15.5 Locations of applicability in the DGR

The closure plugs for both tunnels (DuSO 01, DuSO 02) and the intake shaft (DuSO 03) will be installed at the portals (mouths) of the tunnels and at the mouth of the intake shaft.

5.15.6 Applicability conditions

From the point of view of the safety of the DGR, the component requires:

- Removal of the equipment in the loading and unloading tunnels and the intake shaft.

5.15.7 Subvariants and the subcomponents thereof

The closure plug in this case, with the exception of the intake shaft plug, will consist of concrete blocks, from which a closure wall will be constructed, which will restrain the backfill material during the construction of the plug itself, which will be made from reinforced monolithic concrete.

5.15.7.1 01 Sealing wall made from concrete blocks

Identical to component VY 06.01 (see chapter 5.10.7.2), with the difference that such a sealing wall made from concrete blocks will not be used for the closure of the intake shaft.

5.15.7.2 02 Closure plug made from monolithic reinforced concrete

The composition, requirements and specifications of the C 30/37 XF4 concrete mixture with reinforcement (B 500 B) will be required to fulfil the data requirements as listed in chapter 3.2.1.1.

5.15.7.3 03 Reinforcing steel

Solid, mostly circular steel rods (smooth and ribbed) that are inserted into the concrete so as to enhance its load-bearing capacity and reduce deformation (bars, mesh). The type and amount of the reinforcement for the DGR closure plugs will be specified in the future.

5.15.8 Production/preparation technology

5.15.8.1 02 Closure wall made from concrete blocks

Identical to component VY 06.01. See chapter 5.10.8.3.

5.15.8.2 03 Closure plug made from monolithic reinforced concrete

The production of concrete at the concrete plant and its transport to the mouth of the main mine shafts of the DGR using cement mixer trucks.

5.15.8.3 04 Reinforcing steel

Industrially processed steel (bars, nets).

5.15.9 Installation/construction technology

The closure of the main mine workings will be performed in accordance with the applicable legislation.

5.15.9.1 Closure plugs for the main mine tunnels/shaft on the surface

The method for the closure of the mine intake shaft is set out in section 10 of Czech Mining Authority Decree No. 52/1997 Coll.

Following the backfilling of the intake shaft with aggregate, the closure plug will be placed on foundations that extend from the reinforcement of the intake shaft; the foundations must have at least the same width as the thickness of the plug (i.e. at least 450 mm) and will be deepened up to the soil freeze depth.

The closure of the intake shaft must be planned so that its upper level is (if possible) at ground level.

The closure portal plugs of the two tunnels will be constructed from monolithic reinforced concrete with steel reinforcement.

5.15.10 Estimation of unit prices

The unit price is based on the industry classification manual for 2022 (OTSKP, 2022).

The procedure for the calculation of the price estimation is described in Annex No. 1.

Tab. 53 Overview of the unit prices used for estimating the price of the DGR closure plug

Item name	Unit price according to OTSKP 2022
01 Sealing wall made from concrete blocks	11,500 CZK/m^3
02 Portal closure plug made from monolithic reinforced concrete up to C 30/37 with an XF4 environmental impact degree	8,470 CZK/m^3
03 Portal plug reinforcement steel (rods, mesh)	42,400 CZK/tonne
04 Monolithic reinforced concrete ceiling of a min. compressive strength of class C 30/37 with and XF4 environmental impact degree	10,50 CZK/m^3
05 Ceiling reinforcement steel (rods, mesh)	37,700 CZK/tonne

Tab. 54 Estimate of the price of the intake shaft closure plug

Subvariant name	Volume of concrete	Unit price of the component [CZK thousand]
Intake shaft closure plug with a diameter of 10.5 m and a thickness of 0.45 m made form monolithic reinforced concrete C 30/37 XF4 (reinforcement density 130 kg/m^3)	38.97 m^3	600

5.16 VY 07 Other structural elements

5.16.1 Component details

Name	Other structural elements
Description	Basic parts of the construction process that differ in terms of their materials, purpose and implementation technology and that are firmly connected to the structure or the host environment over the whole of their surface.
Location in the DGR	Underground part of the DGR
Applicability conditions	Engineering-geological conditions, service life and purpose of the mine construction entity. The use of components in specific locations must be assessed from the point of view of the long-term safety of the DGR.
Subvariants	01 Reinforcement 02 Rock bolts 03 Micropiles 04 Grouting 05 Linings and related components
Material	According to the subvariant
Subcomponents	According to the subvariant
Production/preparation technology	According to the subvariant
Production/preparation technology	According to the subvariant

5.16.2 Component requirements

5.16.2.1 External requirements and specifications

The structural-technical design of the DGR must, in accordance with valid legislation, respect the requirements for the safe securing of mine workings (reinforcement) during the excavation, construction and the operation phases of the DGR.

The design parameters of the other structural elements will be based on the needs of the final project design of the DGR according to the 134/2017 report (Grünwald et al., 2018) taking into account the engineering-geological and hydrogeological conditions, the service life and the purpose of the respective structural entity.

Concerning the final design of the DGR, it will be necessary to take into account the interactions between the materials used in the various structural entities and the engineered barriers, the rock environment and the groundwater, which may affect the long-term safety of the DGR, as described in more detail in the 616/2022 report (Večerník et al., 2022).

5.16.2.2 Required safety and technical functions

The required safety and technical functions of the other structural elements will generally depend on the function of the respective structural element.

If the structural elements are not removed (reinforcement), which, for technological and operational safety reasons, is currently not being considered, from the point of view of the long-term safety of the DGR, the choice of the materials used is important with regard to their interaction with the engineered barriers, the rock environment, the groundwater and the other DGR components. This issue is addressed in more detail in the 616/2022 report (Večerník et al., 2022).

Over the long term, it is assumed that the structural elements will gradually degrade and lose their functions. This will result in mechanical impacts on the filling materials of the DGR (the buffer and the backfill), or the WDPs themselves due to the degradation and gradual collapse of these structures. The loss of their weight-bearing capacity will lead to an increase in the loading of the bentonite and the potential for the formation of discontinuities/free spaces/preferential pathways for water flow. When designing the bentonite constructions, all these influences should be taken into account so that they are able to withstand them, i.e. for example the sealing of free spaces via swelling, etc. (Večerník et al., 2022).

Concerning the construction materials, it is necessary to take into account potential chemical, mineralogical and microbiological interactions with the engineered barriers and their possible impact on the long-term safety of the DGR. It is anticipated that the ongoing research of the materials and updates to, and the refinement of, the DGR project design will lead to the convergence of the various requirements and parameters of the engineered barrier and structural element materials.

5.16.2.2.1 VY 07.01 Reinforcement

This structural element will have a temporary stabilising function during the construction (excavation) of the DGR. Its use is expected especially in the near-portal section of the loading and unloading tunnel or, as required, when traversing non-cohesive tectonically damaged parts of the rock mass during the conventional excavation of the tunnels and main corridors.

5.16.2.2.2 VY 07.02 Rock bolts

The use of rock bolts is based on the safety of the DGR project design (Grünwald et al., 2018). These anchoring components will have a temporary stabilisation function during the construction (conventional excavation) of selected parts of the DGR. Their use can be expected especially in the near-portal sections of the loading and unloading tunnel in places with a lower overburden. The use of rock bolts may also be necessary when traversing tectonically damaged parts of the rock mass when excavating the tunnels and main corridors, or when excavating the caverns that will house the technical facilities in the disposal horizon and the HLW RAW disposal chambers.

The optimal technical and economic design of the rock bolt reinforcement of underground structures requires sufficient knowledge of the engineering-geological and geotechnical conditions for excavation. The choice of the most suitable types of rock bolts under given geological conditions will be determined by the price, the required bearing capacity and the so-called “breaking-in time”, during which the rock bolts attain their full bearing capacity.

Analytical, empirical and numerical calculations based on the principle of the finite element or the discrete element method in combination with observational methods are currently used in the design of rock bolt reinforcement with the aim of attaining the optimal technical-economic approach.

5.16.2.2.3 VY 07.03 Micropiles

The required safety and technical functions of the micropiles are the same as for the other structural elements as described in the introduction to chapter 5.16.2.2.

5.16.2.2.4 VY 07.04 Grouting

The function of grouting is to fill any discontinuities and voids in the rock environment to the maximum extent in order to strengthen and seal them. The choice of the grouting mixture is influenced by its price, ease of handling, viscosity (ability to penetrate the rock), stability, resistance to leaching, elasticity (resistance to deformational changes in the surrounding environment) and safety with regard to the risk of contaminating the rock environment and the groundwater in the DGR.

Hence, the success of the grouting process depends on the choice of mixture composition, injection pressure, injection speed, quantity of the injection mixture, the grouting method, the nature of the injected discontinuities, their water capacity and the character of the groundwater, as described in more detail in (Klepsatel et al., 2003).

From the point of view of long-term safety, it is important to choose the material in connection with its chemical compatibility with the engineered barriers, so that its degradation products do not threaten the safety function of the WDP and the buffer, for example, the use of grouting that contains organic materials that may provide nutrients for the development of undesirable microbial activity, as described in more detail in the 616/2022 report (Večerník et al., 2022).

5.16.2.2.5 VY 07.05 Lining and lining components

According to the DGR project design described in the 134/2017 report (Grünwald et al. 2018), when using the TBM excavation method and taking into account the geological conditions encountered in the initial sections of the two tunnels, the use of segment lining or primary lining consisting of reinforcing mesh and shotcrete is considered as an alternative.

When using the conventional excavation method and taking into account the geology encountered in the initial sections of the tunnel, the use of a primary lining consisting of reinforcing mesh and shotcrete is being considered in combination with radial bolts.

With the increasing height of the overburden of the tunnels, it is assumed, due to the nature of the rock environment, that it will be possible to dispense with the necessity for a tunnel lining with additional securing components; the walls will be secured, if necessary, using radial bolts only.

The concrete structural elements will have only a mechanical function (to ensure the stability of the tunnels) during the operational period of the repository.

Their degradation is expected over the long term, including the degradation of concrete mixture additives (e.g. organic substances used as plasticisers or other chemical agents, e.g. as setting retarders or accelerators). The degradation of these materials may lead to the formation of preferential pathways.

The presence of linings and their components will result in the increased activity of the microorganisms present in the DGR. The steel elements will be at risk of microbiologically influenced corrosion; thus, the presence of metal elements may act to locally increase the microbial activity and enhance the formation of corrosion products, while the organic material elements may provide nutrients for the growth of microorganisms and, again, potentiate the microbial activity around the lining, as described in more detail in the 616/2022 report (Večerník et al., 2022).

5.16.3 Component design assumptions

The conceptual design is based on:

- the required dimensions as set out in the 580/2022 report (Dohnálková et al., 2022)
- the anticipated interactions as described in the 616/2022 report (Večerník et al., 2022)
- technical feasibility
- economic feasibility

5.16.4 Component description

5.16.4.1 VY 07.01 Reinforcement

Preceding reinforcement – rods are inserted in advance into boreholes in the tunnel ceiling prior to excavation so as to enhance the stability of the face and to limit possible overcutting.

The technology consists of the use of two basic components, pre-driven reinforcement steel rods and a grouting mixture, which is most often composed of cement-based binders, polyurethane resins or mixtures based on organic-mineral substances. The choice of the grouting material is influenced by the engineering-geological and hydrogeological conditions encountered during excavation and the material safety requirements that must be met with regard to the long-term safety of the DGR.

Currently, insufficient data is available on the engineering-geological and hydrogeological conditions for excavation purposes to allow for determining the final structural design of this component and its construction technology.

However, it can be assumed that the rods will be made from steel with a length of at least 5 m that will be inserted into boreholes.

5.16.4.2 VY 07.02 Rock bolts

Anchor rock bolts as structural elements usually without pre-stressing that are inserted into boreholes so as to anchor areas on the excavation face that are disturbed by the excavation process to more distant areas of the rock that are not disturbed by excavation. Such rock bolts serve to enhance excavation stability.

There are many types of rock bolts available, which differ in terms of their function and the material used. Reinforcing steel is most often used for the production of rock bolts; the use of a composite material – fibreglass – is less frequent.

Since fibreglass anchoring rock bolts are not prone to corrosion and have increased resistance to chemical influences, such rock bolts should be considered for both the temporary and longer-term securing of the face.

Steel and fibreglass rock bolts can be secured using grouting mixtures based on cement or organic-mineral resins or, in the case of steel, also mechanically and hydraulically.

5.16.4.3 VY 07.03 Micropiles

Micropiles are a reinforcing element most often consisting of steel reinforcing perforated pipes that are inserted into small-profile subhorizontal boreholes, which are subsequently filled with a grouting mixture, most often based on cement.

In underground constructions, micropiles are used in the form of a micropile “umbrella” constructed in the vaulting of the mine working in advance of excavation and serve to increase the stability of the rock excavation and the face.

5.16.4.4 VY 07.04 Grouting

Grouting technology is used to improve the properties of rocks and soils by injecting a grouting mixture into cracks or pores in the rock with the aim of the strengthening and sealing thereof.

It is currently used extensively in underground constructions and in the construction industry in general. A wide range of cementitious, chemical and organic-mineral grouting materials are available.

Depending on the grouting pressure applied, grouting in underground structures is classified as low-pressure (backfilling) and high-pressure grouting.

The choice of the grouting technology depends primarily on the engineering-geological and hydrogeological conditions encountered.

When excavating in soil and non-compact heavily-weathered rock environments, which are assumed only in the near-surface parts of the DGR, it is theoretically possible to consider the use of high-pressure or jet grouting so as to improve the excavation conditions.

As the depth and, thus, the quality of the rock environment increases, the use of low-pressure, so-called backfilling, grouting is expected aimed at enhancing the strength of broken rocks or preventing the increased inflow of groundwater. The improvement of the rock environment involves the pressurised filling and sealing of discontinuities with grouting mixtures. However, in order to avoid further degradation, the grouting pressure applied for filling discontinuities around boreholes must not exceed the shear strength of the rock.

The range of applicability of various grouting types according to (Keller, 2019) is shown in Fig. 24.

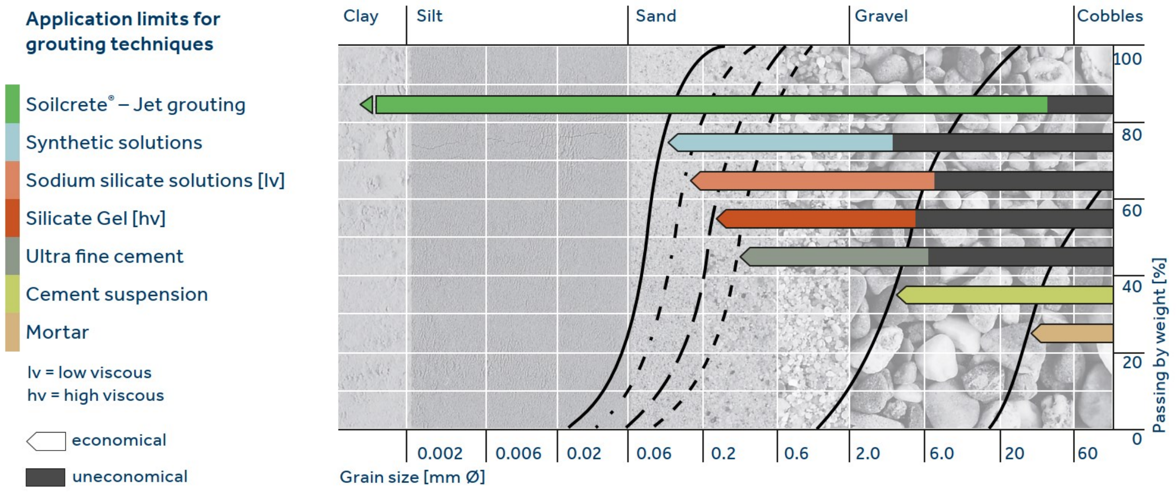

Fig. 24 Range of applicability of various grouting types

5.16.4.5 VY 07.05 Lining and lining components

In terms of the basic distribution of the reinforcement in the concrete, it is assumed that concrete reinforcement and concrete fibres (dispersed reinforcement) will be used in the DGR.

Solid, mostly round, steel bars (smooth and ribbed) are being considered as the concrete reinforcement components; they will be inserted into the concrete in order to increase its load-bearing capacity and reduce deformation. The concrete reinforcement also includes factory-made machine-welded meshes and trusses.

The fibres in the concrete limit the occurrence of cracks and increase the tensile strength and the residual strength following the occurrence of cracks; they will also enhance the resistance of the concrete against explosive spalling due to higher temperatures.

Admixtures comprise chemical compounds that are added to concrete during mixing so as to improve the properties of fresh or hardening concrete.

The primary lining will be prefabricated when excavating the loading and unloading tunnels via the TBM method. The thickness of the segments will be based on a static assessment of the lining. The face surfaces of the segments will be smooth. Joints will be sealed around the entire perimeter with a seal made of natural rubber or moulded plastic. This modification is usually sufficient to achieve the water resistance of the lining. The gap between the face of the cut and the back of the lining will be filled with grouting, which will further enhance the impermeability of the primary lining. Under favourable hydrogeological conditions or conditions with lower water resistance requirements this solution is generally sufficient. Taking into account the fact that, according to the DGR project design (Grünwald et al., 2018), poor hydrogeological conditions and higher requirements for the reliable water resistance of the lining are not anticipated, a two-layer lining with intermediate waterproofing with an inner lining made of monolithic concrete is not being considered.

The primary lining in most cases includes reinforcing arches, which, in addition to static requirements, help to maintain the shape of the excavated profile. Trellis arches made of welded concrete steel are usually used to secure areas excavated conventionally using the NRTM method; this allows for high-quality spraying and, thus, interaction with the concrete.

According to the annexes to the DGR project design (Grünwald et al., 2018), the lining will be made from shotcrete reinforced with 200 mm steel mesh. The exception concerns the loading corridors, where the use of a shotcrete lining is not considered. The reinforcement of the shaft will consist of a concrete lining with a thickness of 450 mm.

In contrast to the DGR project design, depending on the engineering-geological conditions encountered, the shotcrete lining could be reinforced with fibre concrete.

According to the DGR project design (Grünwald et al. 2018), the use of steel arch reinforcement (rolled or trellis) for the purpose of securing the excavated corridors in the DGR remains debatable since the sufficient stability of excavation is assumed throughout the lifetime of the repository, with the exception of the non-cohesive tectonically damaged sections of the rock mass. Under conditions that require enhanced immediate load-bearing capacity, arches made of mining steel reinforcement or rolled steel profiles can generally be used; however, due to handling conditions and, in particular, the service life of the DGR, they are not currently being considered.

According to guidelines for conventional tunnelling (Mosler et al., 2019), monolithic linings are concreted into formwork. Concerning the DGR project design, this concerns the secondary lining of the caverns used for the technical infrastructure, the thickness of which has not yet been determined. Construction usually proceeds using sliding formwork (a formwork truck) and the process allows for the strength class of the concrete or the level of reinforcement to be adapted to the actual geotechnical conditions. With regard to the static height and the required coverage, the minimum thickness for reinforced linings should not be less than 300 mm, for non-reinforced linings less than 250 mm.

It must be noted that the dimensions of the lining will have to be verified in the later stages of the project preparations via static calculations for the specific conditions of selected locations.

5.16.5 Locations of applicability in the DGR

5.16.5.1 VY 07.01 Reinforcement

Preceding reinforcement in the form of rods has a temporary stabilisation role during the construction (excavation) of the underground spaces of the DGR in areas with more complex engineering-geological conditions. Their use is expected especially in the near-portal section of the loading and unloading tunnels (DuSO 01 and DuSO 02), or as necessary when traversing non-cohesive tectonically damaged parts of the rock massif during the conventional excavation of the two tunnels and the corridors (DuSO 05).

5.16.5.2 VY 07.02 Rock bolts

According to the DGR project design (Grünwald et al., 2018), especially in the near-portal parts of the loading (DuSO 01) and unloading tunnels (DuSO 02), with regard to the geology encountered, the use of rock bolts is considered so as to increase the stability of the excavation process. Radial rock bolts will be used in combination with shotcrete reinforced with steel mesh. With the increase in the height of the overburden, improvements are expected in terms of the engineering-geological conditions, which will, theoretically, allow the securing of the tunnels/corridors using radial rock bolts only or shotcrete only without radial rock bolt anchoring.

According to (Špinka et al., 2020a, 2020b; Butovič et al., 2020; Zahradník et al., 2020), if necessary, the use of short anchor rock bolts is also being considered to secure the ceilings of the caverns that will house the technical facilities of the underground part of the DGR (DuSO 10 – DuSO 21). The securing of excavation with radial rock bolts in combination with shotcrete reinforced with steel mesh is also being considered (according to the prevailing engineering-geological conditions) during the excavation of the main (DuSO 05) and connecting corridors (DuSO 06, 07).

5.16.5.3 VY 07.03 Micropiles

Preceding reinforcement in the form of a micropile umbrella has a temporary stabilisation role during the construction (excavation) of the underground spaces of the DGR in areas with more complex engineering-geological conditions. Their use is expected especially in the near-portal section of the loading and unloading tunnels (DuSO 01 and DuSO 02), or as necessary when traversing non-cohesive tectonically damaged parts of the rock massif during the conventional excavation of the two tunnels and the corridors (DuSO 05).

5.16.5.4 VY 07.04 Grouting

Depending on the engineering-geological conditions encountered, the injection grouting of the rock environment may be applied in short sections during the excavation of the loading and unloading tunnels (DuSO 01 and DuSO 02), the intake shaft (DuSO 03), the main corridor (DuSO 05), the RAW disposal chambers RAW (DuSO 11), the confirmation workplace (DuSO 12) and the construction of the technical infrastructure of the underground part of the DGR (DuSO 06, DuSO 07, DuSO 10, DuSO 13 – DuSO 22).

5.16.5.5 VY 07.05 Lining and lining components

Depending on the engineering-geological conditions encountered, the use of shotcrete reinforcement with steel mesh is being considered for the lining of the loading and unloading tunnels (in the initial and near-surface sections), the RAW disposal chambers, the main corridors, the connecting corridors for the technical infrastructure and in the primary lining of the chambers for the housing of the technical equipment. The location and use of the steel arch reinforcement in the DGR will be addressed in future.

When using the TBM excavation method, taking into consideration the engineering-geological conditions, it is possible that the use of segmental lining will be considered to secure the surfaces of the loading and unloading tunnels and main corridors.

According to the DGR project design (Grünwald et al., 2018), monolithic concrete will be used for the lining of the intake shaft. According to (Špinka et al., 2020a, 2020b; Butovič et al., 2020; Zahradník et al., 2020), the use of monolithic concrete is also being considered for the secondary lining of the chambers that will house the technical equipment, including the floors (chamber linings).

5.16.6 Applicability conditions

5.16.6.1 VY 07.01 Reinforcement

Rod reinforcement is generally considered to be the simplest supplementary measure for the securing of tunnel ceilings during the excavation process. It serves to enhance the stability of the excavated faces and limits the extent of over cutting (especially when using explosives). It is most often used in fractured or layered rocks.

The conditions of the applicability of the materials of this component from the viewpoint of the long-term safety of the DGR are described in more detail in the introduction to chapter 5.16.2.2.

5.16.6.2 VY 07.02 Rock bolts

From the point of view of safety during the excavation (construction) of the DGR, the choice of and necessity for using rock bolts will be determined by the engineering-geological conditions encountered.

The deactivation of the rock bolts and their removal prior to the closure of the DGR is currently not being considered for both technological and operational-safety reasons.

The conditions of the applicability of the component materials from the point of view of the long-term safety of the DGR are described in more detail in the introduction to chapter .

5.16.6.3 VY 07.03 Micropiles

From the point of view of safety during the excavation (construction) of the DGR, the choice of and necessity for using micropiles will be determined by the engineering-geological conditions encountered.

Depending on these conditions, micropile umbrellas made of steel perforated injected pipes will be used for the protection of excavated sections where rod reinforcement is not sufficiently safe due to its load-bearing limits.

The deactivation of the micropiles and their removal prior to the closure of the DGR is currently not being considered for technological and operational-safety reasons.

The conditions of the applicability of the component materials from the point of view of the long-term safety of the DGR are described in more detail in the introduction to chapter 5.15.6.

5.16.6.4 VY 07.04 Grouting

The conditions of the applicability of the grouting of the rock environment will be influenced by the engineering-geological conditions encountered with respect primarily to the nature of the rock discontinuities, i.e. layer joints, cracks, fractures and other discontinuities, their water-bearing capacity and the nature of the groundwater.

With regard to the drainage of inflow and technological water, which is primarily being considered as primarily gravity fed, grouting will be used only for water inflows, including pressurised water inflows.

The material and its use will have to be assessed from the point of view of the long-term safety of the DGR.

5.16.6.5 Lining and lining components

The conditions of applicability of linings and their components will depend on the engineering-geological conditions and the service life and purpose of the mine component concerned. The interactions described in the 616/2022 report (Večerník et al., 2022) are assumed for the reinforcement materials and the concrete additives. Commonly used concrete mixtures and the low-pH mixture developed as part of a previous SÚRAO-commissioned study (Pernicová et al., 2019) contain an organic plasticiser. However, considering the amount that is added to the concrete mixtures, this organic material will not exert a significant effect on the long-term properties and degradation process since the concrete structural elements will not have a safety function over the long term. The specific use of these materials will have to be assessed with regard to the long-term safety of the DGR.

5.16.7 Subvariants and the subcomponents thereof

5.16.7.1 VY 07.01 Reinforcement

Rod reinforcement technology involves the use of two basic components, i.e. pre-driven reinforcement injectable steel rods or bars and the injection grouting material, which is usually composed of cement-based binders; however, polyurethane resins or mixtures based on organic-mineral substances may also be used.

The choice of the component materials will depend on the engineering-geological and hydrogeological conditions encountered during excavation. The applicability conditions of these materials from the point of view of the long-term safety of the DGR are described in more detail in the introduction to chapter 5.16.2.2.

5.16.7.2 VY 07.02 Rock bolts

Rock bolts and anchors are generally divided into steel or fibreglass according to the materials used, the choice of which will be influenced by the engineering-geological and hydrogeological conditions encountered during excavation. The applicability conditions of these materials from the point of view of the long-term safety of the DGR are described in more detail in the introduction to chapter 5.16.2.2.

5.16.7.2.1 Steel bolts

The most common types of steel rock bolts in terms of their function are as follows:

- **SN anchors** – reinforcement steel ribbed rods that are inserted into boreholes and fixed with a grouting mixture.

- **MAI anchors** – hollow borehole rods with an external thread and equipped with a disposable drill bit. The external thread is used for connecting individual rods and improving clamping in the grout in the borehole and to allow for the potential for repeated activation when shortening the tunnel face anchors. The hollow profile enables flushing during drilling and the subsequent grouting of the anchor.

Less commonly used types of rock bolts (mechanically clamped) include:

- **Hydraulically clamped rock bolts** – steel pipes with "collapsed" profile. After installation the tube is inflated by high pressure hydraulic media. Two types are used depending on the fate of pressurising media:
  - Type where media is drained after application and the function is ensured only by expanded tube
  - Type where pressurised media is kept after installation and the media ensures the clamping pressure
- **CT anchors** – steel rods with mechanically expandable sleeve. After sleeve activation the anchor cloud be immediately loaded. The grouting can be performed at later stage. The grouting is do trough the anchor. Anchors are typically used in hard rock where mechanical anchoring could be ensured

5.16.7.2.2 Fibreglass rock bolts

Fibreglass rock bolts are often used as a stabilising component when anchoring the rock face. Fibreglass anchors can be more easily dismantled (broken down) during progressive excavation using conventional excavating machines and mechanisms.

Fibreglass anchoring components provide high tensile strength, low elongation under tensile stress and low weights. The synthetic materials used (glass fibres and usually a polyester resin) do not degrade over time, evince enhanced resistance to chemical influences and are not subject to corrosion. However, the organic material contained in these anchoring components can be used by microorganisms as nutrients, which may lead to the more rapid degradation of adjacent components.

On the other hand, fibreglass rock bolts evince a lower shear and bending strength and low torsional stiffness, which acts to limit the use of fibreglass rock bolts in the form of self-tapping rods when drilling in high-strength rocks. The torque necessary to dislodge such rocks may exceed the torsional stiffness of the fibreglass rod component.

5.16.7.3 VY 07.03 Micropiles

Micropile technology, i.e. micropile umbrellas consists of the use of two basic components, a pre-driven reinforcement (micropile) component in the form of a steel pipe and a grouting mixture, which is most often composed of cement-based binders; polyurethane resins or mixtures based on organic-mineral substances are also used. The choice of the grouting material will be influenced by the engineering-geological and hydrogeological conditions encountered during excavation.

5.16.7.4 VY 07.04 Grouting

As previously mentioned, a number of grouting materials are currently used in underground constructions based on both cement and chemical (organic) materials:

- 01 Cement grouting.
- 02 Clay-cement grouting.
- 03 Polyurethane resins
- 04 Epoxy resins.
- 05 Organic-mineral substances
- 06 Acrylic and methacrylate resins and gels.

5.16.7.5 VY 07.05 Lining and lining components

5.16.7.5.1 Steel lining

As previously stated in the applicability conditions, steel arches or arches made of rolled steel profiles are not being considered due to handling complications and, especially, the service lifetime of the DGR.

Truss arches are welded to the desired shape from smooth or ribbed steel in various sizes. Compared to full-wall cross-sections, according to Klepsatele et al. (2003), they have a lower weight, can easily be fitted with meshing, can easily be coupled with anchors and work well with shotcrete. The main disadvantage involves the laboriousness of the production process; moreover, due to the number of welds, it is difficult to reliably verify their quality.

5.16.7.5.2 Concrete reinforcement and other additives

Reinforcement meshing or rod reinforcement are connected to steel reinforcement frames using either rope or screw connectors. Distance components, usually cylindrical in shape, are installed on the face of the lining to ensure reinforcement coverage.

Dispersed fibres can be used to improve the properties of the concrete, the main benefit of which concerns the limiting of the formation of microcracks, reducing the negative effect of concrete shrinkage and increasing the resistance of the concrete, e.g. to the effects of dynamic loading.

Steel fibres are either straight or formed from cold-drawn wire. Fibres cut from steel strips are used less frequently. Wires, which tend to form hard-to-separate clumps during application, are unsuitable for use in shotcrete. Of the range of synthetic fibres available, polypropylene fibres, which significantly increase the fire resistance of shotcrete, are most often used.

Synthetic fibres must be fine enough to allow for their distribution in the concrete using conventional concrete mixers and for sprayed application using conventional spraying equipment.

Glass fibres must be modified so as to ensure elevated resistance in the cement alkaline environment either via the adjustment of the chemical composition of the glass or via lubrication (a very thin coating on the surface of the fibres).

The following additives are used to improve the properties of fresh or hardening concrete:

- Plasticisers and superplasticisers that reduce the amount of water needed to achieve the same workability of fresh concrete.
- Aerating additives which, when added during the mixing of the fresh concrete, create closed air pores that are evenly distributed in the concrete.
- Sealing additives that increase the density of the concrete and reduce its porosity, especially the volume of macropores.
- Additives that retard the setting of the cement so as to increase the transition time of the fresh concrete from the plastic to the solid state.
- Additives that accelerate solidification that shorten the transition time of fresh concrete from the plastic to the solid state.
- Hardening admixtures that accelerate the development of the initial strength of the concrete and may or may not accelerate the setting of the concrete.
- Stabilising additives that reduce the demixing of water in the suspension (bleeding), which occurs via the sedimentation of solid particles.
- Other additives (corrosion inhibitors, grout, biocides and gas-forming, foam-forming and adhesive additives).

In order to improve the properties of both the fresh and hardened concrete, admixtures are used in the form of powdered inorganic substances, including almost inert mixtures (e.g. powdered stone, finely ground limestone) or latent hydraulic admixtures (e.g. concrete fly ash, siliceous fly ash or slag).

5.16.7.5.3 Segment lining

Concrete is the basic material for the production of the lining, mainly in the form of segments reinforced with classic concrete reinforcement, steel dispersed reinforcement or a combination of both types of reinforcement. Basically, the advantage of reinforced concrete components is their high bending capacity, which is, however, associated with the development of cracks, while the advantage of concrete with dispersed steel reinforcement (reinforced concrete) concerns the limitation of the width of cracks at medium (actually existing) levels of bending stress.

The classic reinforced concrete segment consists of concrete and steel. The concrete contains the same components as the other concrete structures. It is possible to determine a number of specific recommendations for the composition of concrete that is suitable for the construction of segments. The cement used is basic, i.e. additive-free and quick-hardening. Reinforced concrete segments are designed from concrete of classes C 30/37.

In the event of a fire in the tunnel, plastic fibres melt, thus creating a network of pores in the concrete into which the resulting water vapour can penetrate, thereby preventing concrete spalling. Hence, it is recommended to add 1 to 3 kg of polypropylene fibers per cubic metre of concrete. Typically, fibres with a diameter of 18 μm are used, the length of which is between 6–12 mm.

The durability of the steel mesh used in the segments is strongly influenced by the permeability of the segments. The thickness of the cover must be determined considering the local conditions, especially the aggressiveness of the surrounding environment. However, a typical coverage value is 20-30 mm. Steel reinforcement can also be protected using paint, plating, epoxy coating or cathodal protection.

5.16.7.5.4 Concrete lining

The lining of mine facilities must fulfil the various required functions both during the construction period and for the expected lifetime of the facility. During the construction period, the basic function of the lining is to ensure the stability of the excavation and the integrity of the supporting rock ring, thereby creating a safe environment for continued excavation. The functions that must be fulfilled by the secondary lining and the design of the concrete mixture recipe for monolithic linings is specified in more detail in (Mosler et al., 2019). Monolithic concrete must fulfil the data requirements listed in chapter 3.2.1.1.

The basic properties and required parameters of shotcrete have been set out mainly in connection with the use of the NRTM method (Hilar et al. 2008). The composition, requirements and specifications of shotcrete must fulfil the data requirements listed in chapter 3.2.2.

The use of reinforcement (concrete and dispersed) and the various additives and admixtures in linings made of shotcrete and monolithic concrete are described in chapter 5.16.7.5.2.

5.16.8 Production/preparation technology

5.16.8.1 VY 07.01 Reinforcement

Steel rods in the form of ribbed solid bars or more often as IBO or SN type bars are manufactured from enhanced B 500B concrete steel.

5.16.8.2 VY 07.02 Rock bolts

The technology for the production and preparation of rock bolts can basically be divided into two groups according to the material used: steel or fibreglass.

5.16.8.2.1 Steel rock bolts

Steel rock bolts are most often produced in the form of injectable anchoring elements of the IBO type or solid rib bars of the SN type. These bars are made of concrete steel (class B 500B).

5.16.8.2.2 Fibreglass rock bolts

Fibreglass solid and injection rods are made of high-quality glass fibres, usually connected to each other with a polyester resin or, in special cases, with vinyl ester or epoxy resin. The combination of these two synthetic materials ensures excellent mechanical properties that do not degrade over time, with increased resistance to chemical influences and corrosion resistance.

5.16.8.3 VY 07.03 Micropiles

Micropile reinforcements in the form of thick-walled perforated tubes are industrially produced from concrete steel.

Cement-based injection mixtures are produced industrially; sometimes, the various industrially produced components of the mixture are mixed just prior to application directly at the construction site.

The various components of grouting mixtures based on polyurethane resins and organic-mineral substances are produced industrially and mixed using special equipment just prior to their application on site.

5.16.8.4 VY 07.04 Grouting

The grouting mixtures considered, including the necessary accessories, are produced industrially. As with the micropiles, the various components of the grouting mixtures are mixed using special equipment just prior to their use on site.

5.16.8.5 VY 07.05 Lining and lining components

Concrete reinforcement comprises industrially processed steel supplied in the form of rods, coils and steel meshing with, possibly, arched truss reinforcement.

The fibres in the concrete comprise industrially processed steel materials, polymers, glass and basalt; the concrete processing additives consist of industrially produced chemical compounds.

The individual segments of the prefabricated lining are produced at specialised construction plants and then transported to the underground part of the DGR - the TBM excavation machine - using a multi-purpose vehicle (MSV - multi service vehicle).

Shotcrete and monolithic concrete will be produced at a concrete batching plant; fibres will be added to the concrete mix following the addition of the aggregate and before the addition of the cement, water and liquid admixture. Chemical additives are added to the mixture during the mixing of the concrete. The fresh concrete will then be transported to the underground part of the DGR using concrete mixer trucks.

5.16.9 Installation/construction technology

5.16.9.1 VY 07.01 Reinforcement

Concerning the stability of the excavated ceilings, it is currently considered that ribbed steel or injectable steel rods of more than 5 m in length will be used, with differing overlaps in the longitudinal direction according to the distance between the steel arch reinforcement and the specific on-site conditions. The rods will be inserted into subhorizontal boreholes, which will then be filled with a grouting mixture. The distance between the rods in the transverse direction will depend on the pertaining engineering-geological conditions.

5.16.9.2 VY 07.02 Rock bolts

Regardless of the material used (glass laminate, steel), the installation of the rock bolts will be ensured using self-tapping anchor components (injectable rods), which will be grouted using grouting compounds following drilling or simultaneously with the drilling process. The most common grouting mixtures are based on cement and organic-mineral sealants.

The choice of a suitable grouting mixture will depend primarily on the engineering-geological and hydrogeological conditions encountered during excavation, on which the requirements concerning their parameters will depend.

The application of the mechanical or hydraulic clamping of rock bolts is currently being conducted to a lesser extent than previously.

5.16.9.3 VY 07.03 Micropiles

Micropile umbrellas are made up of individual micropiles, for each of which a small-profile subhorizontal borehole is first drilled, which is then fitted with a perforated thick-walled steel tube. The injection of grouting materials, most often based on cement, then proceeds via the perforated tubes.

The umbrellas are mostly in the form of elevated profiles (so-called chapels); in certain justified cases, they can be installed directly from the face without elevation, in which case the first few metres of the micropiles are cut or they are not installed in the boreholes for the necessary initial length of the tube.

The parameters of the micropile umbrella (its range, lengths of the micropiles, tube profile, transverse distance of each micropile, etc.) and the choice of grouting mixtures will depend on the specific engineering-geological and hydrogeological conditions encountered.

5.16.9.4 VY 07.04 Grouting

Following grouting, it is always necessary to drill a borehole, which in cohesive rocks serves directly for the fitting of a double or single obturator, which acts to define the grouting floor. Subsequently, the grouting mixture is pushed through the obturator into the borehole itself and its immediate surroundings.

In non-cohesive soils or heavily weathered rocks, a sleeve tube is installed in the grout-filled borehole, which is equipped with perforation in the injected section of the borehole that is covered with rubber “cuffs” that serve as return valves. The grouting mixture is then pushed through the tube into the borehole itself and its immediate surroundings.

Grouting technology can also be applied in the installation of self-tapping rock bolts, the installation process of which is described in more detail in chapter 5.16.9.2.

5.16.9.5 VY 07.05 Lining and lining components

With concern to the conventional excavation method, the concrete reinforcement and built-in steel components must be sufficiently well fixed so that they do not vibrate during the injection of the concrete. With regard to sprayed reinforcement and steel components such as steel truss arches and contact plates, installed using mobile platforms or handling devices, the formation of shadows in the shotcrete cannot be excluded. However, the extent of such shadows can be substantially reduced via the expert guidance of the nozzle. Particular attention must be devoted to the prescribed overlap of the reinforcement meshing, which must (with regard to reducing the appearance of shadows behind the overlapped meshing with a reduced grid) be installed in the cover. If the reinforcement is to comprise two or more layers (e.g. external and internal reinforcing mesh), the second layer of reinforcement can only be installed once the first layer has been sprayed.

Concerning the mechanised excavation method (TBM with a shield), after each excavation procedure, a new ring is constructed in the rear part of the machine shield using an erector (segment installer), which serves as support for the machine during excavation and forms a hermetically sealed, waterproof tunnel structure.

From the structural point of view, the vaults of the chambers for the technical infrastructure will, depending on the geotechnical conditions, be based either on belt footings or on a lower arch; this will be decided in the future. The profiling of the primary lining and installation of the reinforcement is performed using platforms. The concreting of monolithic linings proceeds in the form of blocks of concreting in a sliding formwork. A curing/maintenance truck is used to treat the concrete after it has been removed from the formwork.

5.16.10 Estimation of unit prices

5.16.10.1 VY 07.01 Reinforcement

The unit price is based on the industry classification guide for 2022 (OTSKP, 2022). In the future, it will depend on the choice of the type and length of the rods based on the specific engineering-geological conditions (Tab. 55).

Tab. 55 Unit price of the reinforcement - rods

Item name	Unit price according to OTSKP 2022
Rods with a diameter of 32 mm and length of up to 6 m	977 CZK

5.16.10.2 VY 07.02 Rock bolts

The unit prices are based on the industry classification guide for 2022 (OTSKP, 2022). In the future, they will depend on the choice of the type and length of the rock bolts based on the specific engineering-geological conditions (Tab. 56).

Tab. 56 Unit prices of the rock bolts and related components

Item name	Unit price according to OTSKP 2022
Boreholes for the rock bolts and anchors underground up to 12 m, class III, diameter up to 50 mm	2,420 CZK/m
Rock bolts mechanically clamped underground, length up to 2.5 m (loading capacity over 200 kN)	904 CZK
Steel rock bolts injected underground, length up to 2.5 m (loading capacity up to 200 kN)	1,230 CZK
Rock bolts glued underground, length up to 2.0 m (load capacity up to 200 kN)	851 CZK
Rock bolts hydraulically clamped underground, length up to 2.5 m (loading capacity over 200 kN)	1,420 CZK
Laminate rock bolts underground, length up to 2.5 m (loading capacity over 200 kN)	1,420 CZK

5.16.10.3 VY 07.03 Micropiles

The unit prices are based on the industry classification guide for 2022 (OTSKP, 2022). In the future, they will depend on the choice of the type and length of the micropiles based on the specific engineering-geological conditions (Tab. 57).

Tab. 57 Unit prices of the micropile umbrellas and related components

Item name	Unit price according to OTSKP 2022
Micropile set, diameter up to 150 mm underground for the protective umbrella	2,950 CZK/m
Borehole drilling for the micropiles underground up to 12 m, class III, diameter up to 150 mm	2,960 CZK/m

5.16.10.4 VY 07.04 Grouting

The unit prices are based on the industry classification guide for 2022 (OTSKP, 2022). In the future, they will depend on the choice of the type and extent of the grouting based on the specific engineering-geological and hydrogeological conditions (Tab. 58).

Tab. 58 Unit prices of the grouting and related components

Item name	Unit price according to OTSKP 2022
High-pressure grouting using cement binders underground	21,300 CZK/m^3
High-pressure grouting using clay binders underground	16,800 CZK/m^3
High-pressure grouting using chemical binders (based on polyurethane and epoxy resins, organic-mineral materials, acrylic and methacrylic resins and gels) underground	30,200 CZK/m^3
Boreholes for grouting and monitoring underground up to 12 m, class III, diameter up to 50 mm	2,420 CZK/m

5.16.10.5 VY 07.05 Lining and lining components

The unit prices are based on the industry classification guide for 2022 (OTSKP, 2022). In the future, they will depend on the choice of the type of lining and its components based on the specific engineering-geological conditions.

Estimations of the prices of the lining of the loading and unloading tunnels (DuSO 01, DuSO 02), intake shaft (DuSO 03) and backbone corridors (DuSO 05) from shotcrete reinforced with steel meshing are provided in Tab. 59

Tab. 59 Unit prices of the linings and related components

Item name	Unit price according to OTSKP 2022
Final tunnel lining using reinforced concrete sections up to C30/37	18,750 CZK/m^3
Truss arches welded from concrete steel	56,900 CZK/t
Excavation of a tunnel made from steel mesh and trusses in wet rock	40,900 CZK/t
Final tunnel lining made from shotcrete	9,130 CZK/m^3
Final tunnel lining made from shotcrete up to C 25/30, thickness up to 200 mm	1,820 CZK/m^2
Final tunnel lining made from shotcrete with steel fibres up to C 25/30, thickness up to 200 mm	2,670 CZK/m^2
Final tunnel lining made from shotcrete with artificial fibres up to C 25/30, thickness up to 200 mm	1,870 CZK/m^2
Reinforcement of the final lining of the tunnel using meshing	36,500 CZK/t
Final tunnel lining with reinforced concrete up to C 25/30	9,340 CZK/m^3
Formwork for the final tunnel lining	1,980 CZK/m^2
Final lining of the bottom of the tunnel with reinforced concrete up to C 25/30	8,450 CZK/m^3
Formwork for the final lining of the tunnel bottom	1,840 CZK/m^2
Tunnel reinforcement using concrete steel 10505, B500B	54,600 CZK/t
Final lining of the shaft made from shotcrete	10,600 CZK/m^3
Formwork for the final lining of the shaft	2,650 CZK/m^2
Final lining of the shaft made from reinforced concrete	12,100 CZK/m^3
Reinforcement of the final lining of the shaft using meshing	36,500 CZK/t
Reinforcement of the final lining of the shaft using concrete steel 10505, B500B	54,600 CZK/t

6 Conclusion

This report presents the conceptual design of the backfilling and other engineered components of the future Czech DGR, and follows on from previous project designs (report no. 134/2017, Grünwald et al., 2018), taking into consideration the previous outputs of the Backfill project (report no. 616/2022, Večerník et al., 2022). The design proposals took into account the safety, technical and economic aspects, as well as current legislation.

This is the initial version of the conceptual project design and is intended to serve as one of the inputs for the safety and thermo-technical calculations and the design solution and R&D preparations for the DGR. It is expected that the report will be updated based on the results of the concept assessment.

From the point of view of safety, the components outlined above can be divided into two basic groups - components with a safety function (buffer, backfill, RAW chamber backfill and other backfilling) and components with a supporting function (plugs and structural elements).

*Note: Most of the support and structural elements will require **site-specific assessment**s from the point of view of long-term safety. In the future, it will be necessary to prepare a methodology for assessing the usability of auxiliary components from the point of view of long-term safety.*

VY 01 Buffer

The **backfilling of the disposal boreholes** component is included in the engineered barriers with a safety function group and has been considered according to several variants for both the horizontal and vertical disposal methods.

The component was considered in terms of three variants – 2 for the horizontal system (differing diameters of the well) and 1 for the vertical system. The various subvariants differ in terms of the form of the backfilling material. The preferred subvariant is the use of compacted bentonite in the form of blocks with a backfill of pelletised material in order to ensure the attainment of the required dry density of the bentonite.

This method will most likely be the preferred option provided that the pelletised material technology can be perfected in the future. However, further technological development is currently required.

VY 02 Backfill

The **backfilling of the loading corridor** component is included in the engineered barriers with a safety function group and has been considered in terms of one technological variant for the vertical disposal system (the horizontal system does not include loading corridors). The subvariants differ only with respect to the dimensions of the corridors according to the type of technology used for excavation; however, the backfilling itself is identical. The use of pelletised bentonite is assumed. Current pelletised bentonite technology is sufficient for the needs of the backfill in this case.

VY03 Backfilling of the RAW chambers

The **backfilling of the RAW chambers** component is included in the engineered barriers with a safety function group and has been considered in terms of two basic variants, determined according to the construction technology – full backfilling and partial backfilling. Since the material that will be used to backfill the RAW chambers has not yet been decided, two basic variants were developed for cement and bentonite backfilling. The final decision will have to be supported by a safety assessment, which will be required to take into account the nature of the RAW to be disposed of, the WDP and the location of the chambers with regard to the SNF disposal sections.

From the technological point of view, partial backfilling can be recommended as the preferred option due to the greater certainty of the high-quality backfilling of the chambers. It will be necessary to ensure the homogeneity of the backfill and, in view of the experience gained from the stabilisation of the chambers at the Richard and Bratrství repositories, the flow of the concrete mixture from the opening of the filling pipe is guaranteed up to a distance of 8 m (MP.38). If bentonite is used as the backfill material, the chambers or chamber segments will be backfilled gradually in accordance with the selected backfilling technology, taking into account the RAW disposal mode.

VY 04 Backfilling of the disposal horizon

In terms of its technical and functional design, the **backfilling of the disposal horizon** component is the same as the backfilling of the loading corridor. However, the geometric arrangement differs, i.e. the transverse profile is based on the DuSO function. Furthermore, less emphasis is placed on the thermal conductivity of the material and the possibility exists of leaving some of the supporting elements in place following a prior assessment of the effects on the long-term safety.

VY 05 Backfilling above the disposal horizon

In terms of its technical and functional design, the **backfilling above the disposal horizon** component is based on the backfilling of the disposal horizon component. The position of the backfilling will depend on one of two variants - medium depth and subsurface. The medium depth variant, in turn, has two subvariants according to the backfilling material used – pelletised bentonite or a mixture of bentonite and aggregates (the preferred variant). The subsurface variant considers aggregates only.

VY 06 Plugs

The plugs, which comprise engineered components, will have only an operational function, i.e. to seal the loading corridors or horizontal disposal boreholes at the disposal horizon level, according to the SNF disposal concept finally adopted. In the medium term, they will serve to seal both the RAW chambers and their access corridors. With the exception of the shaft plugs at the disposal horizon level and on the surface in the form of a sealing roof and the sealing plugs of both tunnels, all the plugs will be made from shotcrete in combination with a sealing wall of concrete blocks.

VY 07 Other structural elements

The rods, which comprise one of the engineered components, will have only an operational function and will be installed in advance in boreholes in the tunnel ceiling prior to excavation, thus increasing the stability of the face and limiting possible overcutting. The rod technology consists of the use of two basic components, pre-driven reinforcement injectable steel rods or bars made of concrete steel and the borehole grouting mixture.

The rock bolts and anchors can generally be divided into steel or fibreglass components according to the material selected. The choice of the materials used will be influenced by the engineering-geological and hydrogeological conditions encountered during excavation. The use of radial rock bolts will be in combination with shotcrete reinforced with steel meshing.

The micropile umbrella technology consists of the use of two basic components, pre-driven reinforcement (micropiles) in the form of steel tubes and a grouting mixture. The umbrellas will mostly be installed from elevated profiles (so-called chapels), whereas, in some justified cases, they could be installed directly from the face without elevation, with the fact that the first few metres of the micropiles will be cut or will not be installed in the boreholes for the necessary initial length of the pipe.

The grouting materials comprise engineered components that will primarily serve for temporary stabilisation purposes during the construction and operation of the DGR.

A wide range of cementitious, chemical and organic-mineral grouting materials are currently used in underground constructions and in the construction industry in general. Their use is influenced by the engineering-geological conditions, which primarily include the nature of the rock discontinuities, i.e. layer joints, cracks, fractures and other discontinuities, their water-bearing capacity and the nature of the groundwater.

The specific use of these components will have to be assessed in advance, including from the long-term safety perspective.

The lining and its related components comprise an engineered component that will have only an operational function, i.e. it will ensure the stability of the excavated sections during the construction and operation of the DGR. If tunnelling is performed using the TBM with a shield, the lining will be prefabricated. In other cases, shotcrete and/or monolithic concrete will be used.

The use of reinforcement (concrete and dispersed) in linings made of shotcrete and monolithic concrete will be influenced by the engineering-geological conditions encountered. The use of arches made of steel ductile reinforcement or arches in the form of rolled steel profiles is not envisaged.

The specific use of the lining will also have to be assessed in advance from the point of view of long-term safety.

Uncertainties of the conceptual design

During the consideration of the conceptual design, it was necessary to work with the uncertainties inherent in the input parameters and the more general requirements concerning the functions of the various components.

The conceptual design set out herein should, therefore, be considered to be an initial proposal, which will be refined in the future.

No specific bentonite has yet been selected for the buffer and backfill for the DGR. The quality of the material will be decisive in terms of the selection process.

Moreover, the precise requirements in terms of the bentonite parameters that will impact the chosen technical design approach (and vice versa) have not yet been established.

The issue of the dry density of the bentonite remains to be resolved. From the microbiological point of view it will be essential to limit the microbial activity to the maximum.

Furthermore, it will be necessary to verify the behaviour of all the most important materials in terms of their mutual long-term interaction under DGR conditions from the point of view of microbiology and geochemistry/geotechnics. It will only then be possible to define the suitability of their actual use in the DGR for SNF and RAW.

Uncertainties of the component prices

The estimation of the prices of the bentonite-based backfilling is based on the prices stated in the 134/2017 report (Grünwald et al., 2018), as increased by the inflation rate in 2018-2022. The price was converted to kg of dry material. The greatest uncertainty concerns the prices of the disposal technology, which will be specific to the Czech DGR. Currently, no similar facility exists that could be used for price benchmarking purposes.

The estimation of the prices of the cement backfilling is based on expert estimations and experience obtained from similar construction projects (the Richard and Bratrství repositories) at 2022 price levels. The unit prices include the price for the material, including the preparation and installation of the mixture.

Other prices are based on those listed in the industry classification guidelines for 2022 (OTSKP, 2022). However, this classification manual is not directly intended for the needs of the DGR. It is, therefore, recommended that these prices be increased by at least 25% for the calculation of the costs associated with the DGR.

Legislation

The construction, operation and closure of the DGR will be conducted fully in accordance with the applicable legislation. Mining legislation is currently based on the needs of the mining industry; therefore, its direct application with concern to the future needs of the DGR is not currently ideal and fails to address some of the aspects of the DGR.

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