FEASIBILITY STUDY OF PROCESS PARAMETERS PROVIDING RW CLASS 2 AND 3 DISPOSAL IN THE PJSC PIMCU'S UNDERGROUND MINES

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Countries with nuclear power are searching for new opportunities to address the challenge of radioactive waste (hereinafter — RW) management which is seen as a priority area for their research. In accordance with the classification established by the Decree of the Government of the Russian Federation № 1069 of October 19, 2012, RW Class 2 shall be disposed of in DGD built at a depth of over 100 m, whereas RW Class 3 can be disposed of in near-surface disposal facilities at a depth of up to 100 m. Joint disposal of non-heat-generating Class 2 and 3 RW in mining chambers at great depths assuming certain safety arrangements implemented in the chambers is seen as a promising research area. RW disposal in existing underground excavations provides cost reduction due to the use of existing surface and underground infrastructure facilities. To evaluate the potential of DGD RW siting within already existing underground excavations, research and safety assessments, including the long-term ones, should be performed to check their compliance with the requirements set for RW disposal facilities. This paper presents engineering technologies allowing to start the process of safety demonstration assuming RW Class 2 and 3 disposal in underground mines. It presents mining and geological rock characteristics evaluated for the Streltsovskaya caldera deposits confining the PJSC PIMCU uranium mines. The paper also discusses the main geomechanical properties of paste backfilling based on uranium ore processing byproducts, the parameters of a rope-injection method used to strengthen the fractured rocks, to eliminate the cracks and to minimize the groundwater and gas flows. It also presents the processes implemented to upgrade the waste chambers located at depths of up to 1,000 m and more.

Keywords: *radioactive waste management, radioactive waste, RW containers, waste chambers, underground space, rope-injection rods, RW storage facilities, RW disposal, fractured massif strengthening, rocks, paste backfilling, uranium ores, radon release.*

Introduction

Deep geological disposal of radioactive waste has been studied for several decades by nuclear power countries. For these purposes, underground research facilities (URFs) have been established to perform large-scale tests. Designs of underground facilities intended for long-term storage of low- and intermediate-level waste provide for the excavation of several tunnels in homogeneous low-permeable rocks either with vertical shafts or inclined drifts, various layouts for RW transportation and stacking, as well as ventilation and water drainage systems. Several spatial layouts were proposed for DGD excavations depending on the characteristics of the RW planned to be disposed of there, site location, rock properties and the RW volume subject to disposal [1].

Underground excavations provide safe RW storage and disposal in Spain, France, Sweden, Finland and other countries. At the Konrad mine (Germany), a DGD designed for non-heat-generating low- and intermediate-level waste is being established in a layer of ferruginous terrigenous-carbonate rocks at depths of up to 800 meters. New chambers with a length of up to 1,000 m and a cross section of up to 40 m^2 will be used for RW disposal purposes. The space around the RW packages stacked in three tiers (about 40 % of the excavation capacity) will be backfilled with a sorbing buffer. The total design capacity of the facility will amount to 1 million m^3. Bátaapáti repository (Hungary) was designed for low- and intermediate-level waste. Its design capacity amounts to 20 thousand m^3. There is an annular transportation layout with dead-end entry chambers intended for RW container emplacement. The cross section of the chambers is about 40 m^2, the total length is 1,000 m [1].

In the Russian Federation, the first near-surface facility for solid Class 3 and 4 RW disposal (NSDF) was commissioned near the city of Novouralsk in 2016. Two NSDF — in the vicinity of Ozersk city with a design capacity of up to 200 thousand m^3 and the Seversk city with a capacity of up to 150 thousand m^3 — are under construction. A project has been developed to establish a deep disposal facility for Class 1 and 2 RW (DGD) in the Nizhnekanskiy rock mass composed of high-strength monolithic rocks (Krasnoyarsk Territory). In accordance with the developed and approved Strategy for DGD development, the first stage of the project provides for the construction of an URF [2—5].

Characteristics of Streltsovskaya caldera rocks

Sedimentary-volcanogenic unit of the Streltsovskaya subsidence caldera mainly consists of felsite, conglomerate, gravelstone, trachydacite, basalt, andesite-basalt and their lava breccias. According to the scale proposed by prof. M. M. Protodyakonov, the corresponding rock strength coefficients vary from 8—10 (for sandstones and tuffs) to 10—18 (for trachydacites and granites) [6]. The strength of the ore and the host rocks differ insignificantly.

Their volumetric weight on average was taken equal to 2.45 t/m^3, porosity varies from 0.11 to 14.7 %, moisture content in natural occurrence — 2.89—3.14 %. Due to blast-hole and borehole breaking, rock and ore loosening coefficient averaged to 1.6.

Outside the fault zones, the rocks are characterized as medium-resistant, excavation operations can be performed with no fastening or providing the use of lightweight lining (Table 1) [6].

***Table 1.** Characteristics of fractures in the rocks of the Streltsovskoye uranium ore field*

Group by the fracturing degree	Name of the group	Size of an elementary structure block, d_{av}, m	Unit weight of the group, %
I	corrugated	less than 0.05	3–30
II	intensely fractured	0.05–0.15	30–50
III	fractured	0.6–0.30	10–50
IV	slightly fractured	more than 0.30	10–20

Small-pebble conglomerates and gravel stones have good stability: during mine excavation, these are required to be fastened only in certain areas — at the intersections with large faults. Trachydacites are broken by fractures spreading in different directions with an average size of an elementary block of 15—25 × 60 cm. Outside the fault zones, excavation activities can be performed without fastening given a short service life of the excavation itself. During long-term operation of excavations, reinforced concrete rods are used for fastening purposes, which may involve roof tightening with a mesh and concreting depending on the rock fracturing degree. The felsite is disturbed by columnar separation. A characteristic feature of these rocks involves the formation of pinholes in the walls and the roof of excavations in case of drilling and blasting method application.

In accordance with rock fracturing characteristics, sites of group IV (Table 1) composed of small-pebble conglomerates, gravel stones, trachydacites, basalts, andesite-basalts are seen as most preferrable and adequate for chamber excavation intended for Class 2 and 3 RW disposal; their share accounts for 10—20 % (Figure 1) [6].

From a hydrogeological perspective, the Streltsovskaya subsidence caldera is distinguished by pronounced autonomy. The waters of Quaternary deposits have no hydraulic connection with the underground waters of the deposit area, therefore, radioactive mine water does not contribute to the contamination of the surrounding artesian basin.

Reservoir-fissure waters of the weathering crust and fissure-vein waters of fault zones do not have any hydraulic connection between themselves (Table 2) [8].

Considering all underground space available in PJSC PIMCU mine, considered most suitable are the

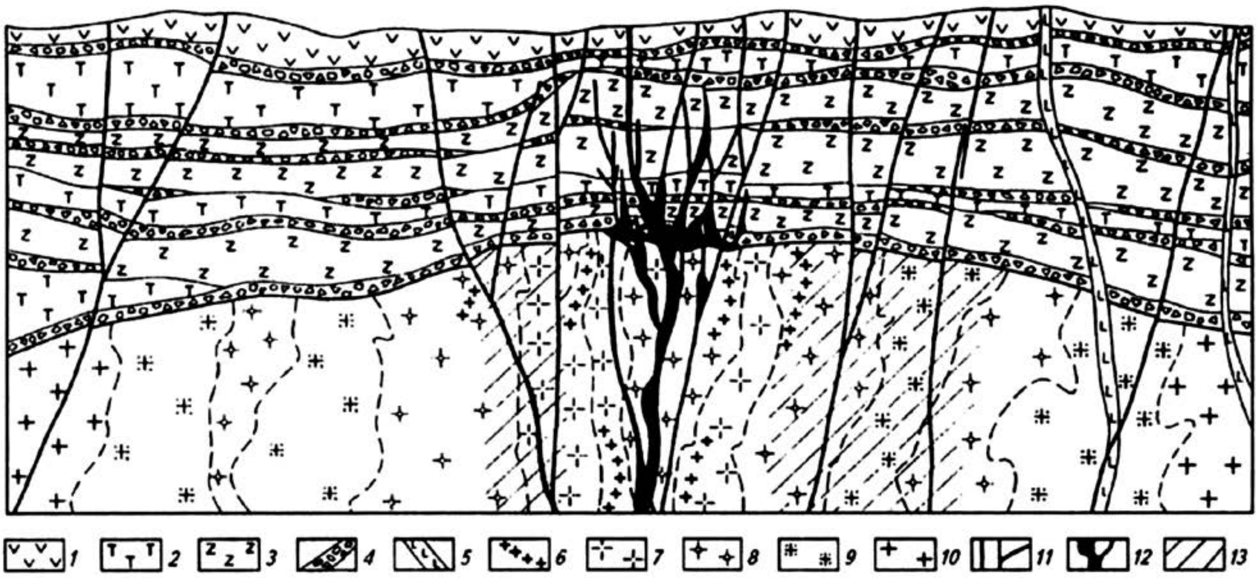


Figure 1. Geological section of the Streltsovskaya caldera: 1— felsite; 2 — andesite-basalt; 3 — trachydacites; 4 — conglomerates, gravelstones, sandstones, 5 — mafic dikes, 6—10 — granitoids (6 — aplitoid, 7— pegmatoid, 8 — leucocratic, 9 — biotite, 10 — granite gneisses), 11 — faults, 12 — ore bodies, 13 — low uranium content areas

Table 2. Streltsovskaya caldera, hydrogeological characteristics

No	Type of groundwater	Depth, m, rock types	Background concentrations of radioactive substances, g/l	Hydraulic connection with other types of water
1	Reservoir-pore waters of alluvial and proluvial Quaternary deposits	20–40, sedimentary rocks	Outside the mining area U – $1.6 \cdot 10^{-5}$ ($4.06 \cdot 10^{-4}$ Bq/kg); Ra – $1.2 \cdot 10^{-11}$; Rn – 110·Bq/kg	Limited distribution, not connected with the groundwater flows in the deposit area
2	Reservoir-fissure waters of the weathering crust composed of sedimentary volcanogenic rocks	50–200, sedimentary rocks	U – $9 \cdot 10^{-7}$ (up to $2 \cdot 10^{-4}$ in ore zones); Ra – up to 740 Bq/kg; K_f=0.0033 m/day pH – 7–8	There is no hydraulic connection with the waters of the tectonic disturbance zones constituting to sedimentary-effusion granitoid intrusions
3	Fissure-vein waters of fault zones constituting to sedimentary-effusion granitoid intrusions	200–360 and more, granites	U – $22.8 \cdot 10^{-3}$ (25.4 Bq/kg); Ra – 6,000 Bq/kg. Below the 300 m zone: U – $5 \cdot 10^{-4}$ (up to 12.7 Bq/kg); Ra – 37 Bq/kg	No hydraulic connection with the waters of the weathering crust composed of sedimentary-volcanogenic rocks

abandoned chambers of mines No. 1 and Glubokiy with a total void capacity of up to 1.5 million m^3 [9].

The choice of RW disposal methods, designs of disposal structures, structure and properties of safety barriers depends on the characteristics of RW intended for disposal, their volume, environmental parameters in the siting area and the DGD safety assessment findings [11]. In accordance with the requirements of the Government Decree No. 1069 of October 19, 2012, RW disposal should be performed in:

- Deep disposal facilities in case of Class 1 and 2 RW;
- Near-surface disposal facilities in case of Class 3 and 4 RW — facilities located above the ground surface level, at the same level with the ground surface and below the ground surface level at a depth of up to 100 m.

Repository construction at the sites located directly in active faults or geodynamic zones is prohibited. Faults are available on the territory of mines No. 1 and Glubokiy: Streltsovsky, East zone, Central zone, Malo-Tulukuevskaya zone formed in the Paleozoic, Mesozoic and Cretaceous periods about 100 million years ago and earlier, which are not included in the list of active faults compiled by the Geological Institute RAS [7].

Repository construction is prohibited at the sites, the seismicity of which is characterized by the intensity of a maximum design earthquake exceeding 8 points on the MSK-64 scale. On the OSR-2016-D map, mines No. 1 and Glubokiy are located in the zone with a maximum earthquake intensity of 7. Their return period accounts for 1,000 years. In a 50-year period, the calculated intensity may be exceeded with a probability of 0.5 % [27].

Class 2 and 3 RW (non-heat generating RW) disposal in abandoned chambers of underground mines with all necessary preliminary operations implemented beforehand provides for the establishment of a safety barrier system [11], involving:

1) containers considered as the main insulating barriers made of metal or reinforced concrete. The use of NZK-150-1.5P containers is considered as a design option [12]. Containers are to be stacked in up to 9 tiers with a 1—2 m wide gap between the walls, which is needed to move crane supports and for personnel access (it is advisable to use loaders for container stacking in up to 4 tiers);

2) paste backfilling the voids between containers and chamber walls based on materials from uranium ore processing (RW Class 6) characterized with radiation resistance (contain natural nuclides), low initial viscosity (< 400 mPa·s) providing opportunities for pipeline-based supply and backfilling of the voids in the chambers, and the required strength after its hardening;

3) rope-injection hardening of host rocks around the chambers with hardening compositions being injected into the fractured rock mass. The reinforcing material from drilled holes or wells penetrates the cracks with an aperture of up to 0.06 mm, adhesion to the rock occurs and its own strength exceeds the tensile strength of the rock, the composition retains strength over time, does not dissolve in water and prevents the seepage of water and gas flows;

4) siting of RW storage facilities at great depth — up to 1,000 m and more: a thick mass of overlying rocks composed of granites, conglomerates, gravelstones, etc. characterized with long-term geochemical stability, high strength and thermal conductivity, low porosity.

Containers for RW Class 2 and 3 disposal

Figure 2 shows the shapes and dimensions of some RW containers manufactured by JSC 345 Mechanical Plant [12].

NZK-150-1.5P reinforced concrete containers (1.65 × 1.65 × 1.375 m) are recommended for RW disposal in abandoned treatment chambers with a steep dip and large and medium capacities. The internal capacity intended for RW emplacement may be up to 1.5 m^3; if some voids are available (surfaces of seismic and shock waves reflection), these should be filled with concrete. Usually, RW emplacement process provides for container kits involving various container types.

Paste backfill based on materials from uranium ore processing

Leading mining countries and our country, in particular, commonly use paste to backfill the voids in abandoned underground chambers. For more than two decades the PASTE international community has been holding annual conferences, publishing collections of reports discussing the research in this area and practical application of this method.

In the underground chambers of PJSC PIMCU, the space between the waste container and the walls is proposed to be filled with a paste filling produced based on the materials from uranium ore processing (with over 2.5 million m^3 of these generated annually by GMZ) with an addition of some flocculants and hardening additives (cement, fly ash, sand-gravel mixture (SGM), crushed rock).

Properties of this paste filling were studied by JSC VNIPIpromtekhnologii and PJSC PIMCU [13, 14]. Paste filling is a gel-like mineral mass with a density of up to 1.2—1.8 t/m^3. It does not enter into chemical reactions with metal and concrete containers and gains compressive strength of over 1.0—2.0 MPa within 28—60 days.

Solid fraction of the pulp is mostly composed of sludge particles (Table 3), their thickening is driven by the flocculants applied. Considered most acceptable are Magnaflok (grades 919, 155, 10, 342), as well as BEESFLOK (grades K6732), FLONOR (grades MA-19, MA-20, MA-22, RA-265E, RA-287E, RA-287X), PAA PCR [13].

KMZ NZK Drum KRAD

Figure 2. Containers used as RW packages

***Table 3.** Pulp from the tailings resulted from carbonate uranium ores processing and the granulometric composition of their solid fraction (according to the Central Scientific Research Laboratory of PJSC PIMCU) [14]*

Name of the material	Granulometric content, % with a particle size, mm					
	+0.2	−0.2–+0.1	−0.1–+0.07	−0.07–+0.05	−0.05–+0.02	<0.02
Solid fraction of the resulted pulp	0	8±2	12±2	16±2	4±2	40±2

In the vat thickener, flocculant is added to consolidate tailing pulp sludge particles into large floccules (Figure 3) [14].

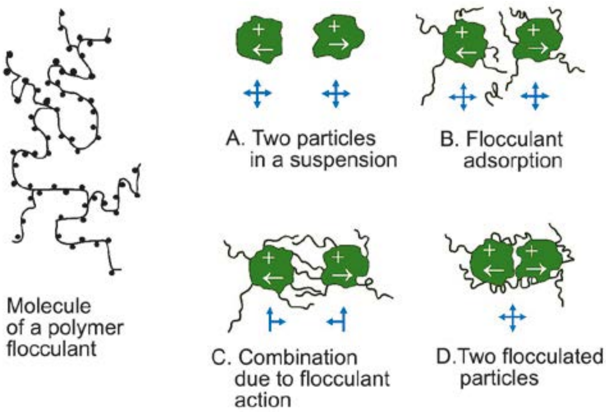


Figure 3. Formation of large floccules from flocculant monomers and tailing pulp sludge

Paste filling is characterized by such process parameters as rheological properties (viscosity, shear resistance, density) and strength. The rheological properties of the paste material were measured by the cone slump method (Figure 4) [13, 14].

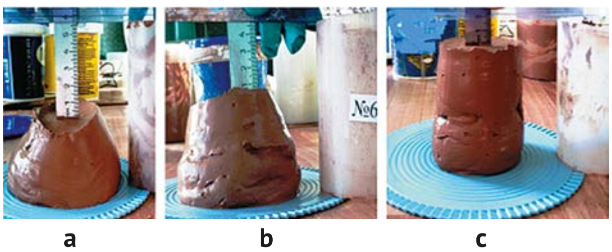


Figure 4. Rheological properties of the paste measured by the cone slump method given solids content of: a) 53%, b) 58%, c) 62%

The tailing pulp generated at the hydrometallurgical plant (GMZ) has a solid content of 34.4%; after thickening, the paste backfill contains 45—65% of solids and may be adjusted depending on the task at hand.

Vat thickeners are cylindrical tanks with conical bottom and a diameter of 10 to 50 m. The resulting heavy floccules are deposited at the bottom of the thickener: the slower this process occurs, the denser is the paste deposited at the bottom, which is due to the free water being squeezed out from it. The clarified water is displaced from the pulp to the upper level of the thickener and is recycled.

Figure 5 presents the process flowchart and the stages of paste fabrication in a vat thickener [13].

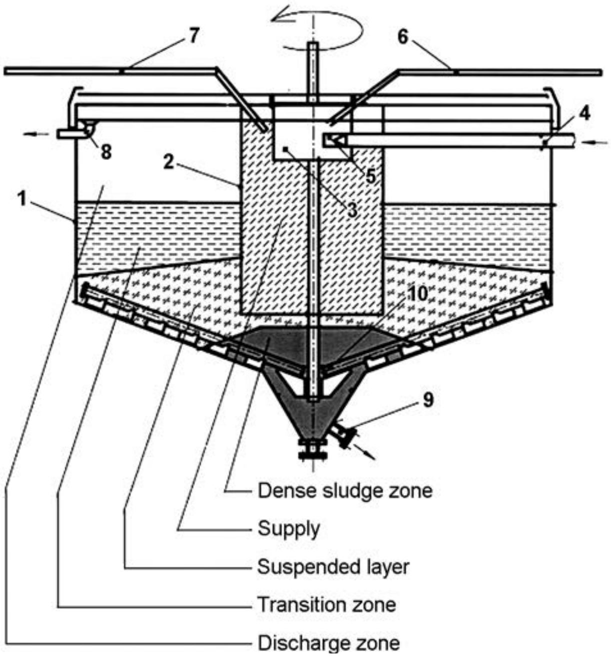


Figure 5. Layout of the thickener tank:
1 — thickener tank, 2 — flocculation chamber,
3 — mixing chamber, 4 — supply pipeline,
5 — tangential inlet to the mixing chamber,
6 — first-stage flocculant pipeline,
7 — second-stage flocculant pipeline, 8 — drain box,
9 — sludge discharge, 10 — sludge removal mechanism

Paste filling is pumped through a pipeline in the form of a dense homogeneous mass with a dense core in the center and a liquefied structure along its periphery, which is explained by the concentration of unipolar flocculant ions at the paste — pipeline interface, thereby providing a lubrication effect enabling the transportation of a dense paste over long distances with no additional pumping stations needed (Figure 6).

Figure 7 presents the changes in the compressive strength of a hardened paste backfill based on materials from carbonate and aluminosilicate uranium ore processing by PJSC PIMCU over time (14, 28, 56, 180 days) [13, 14].

To increase the strength, cement, sand and gravel mix, fly ash, crushed rocks are added to the paste backfill. The hardening agents are introduced into a mixer fitted downstream the tank thickener or

Figure 6. Pipeline transportation of paste filling, solids content of over 45—65%

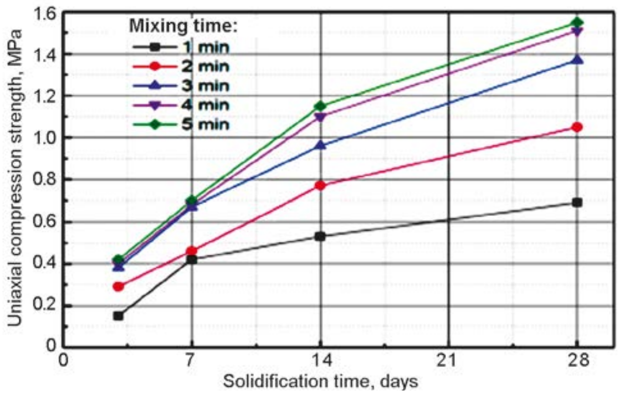


Figure 8. Dependences between the compression strength of a paste filling and the mixing time of the components

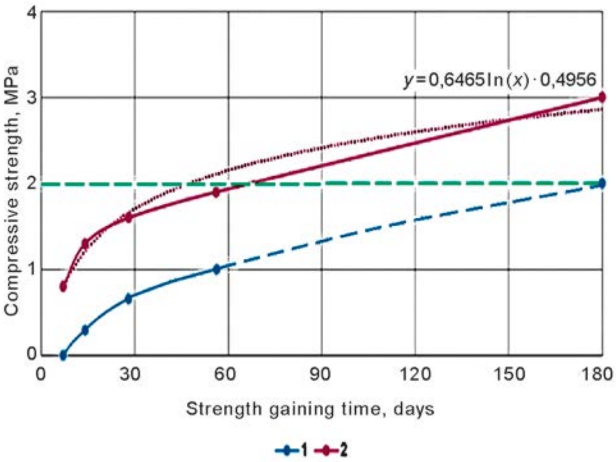


Figure 7. Compression strength (MPa) of paste samples based on uranium ore processing materials with an addition of cement (10%): 1 — carbonate ores, 2 — aluminosilicate ores

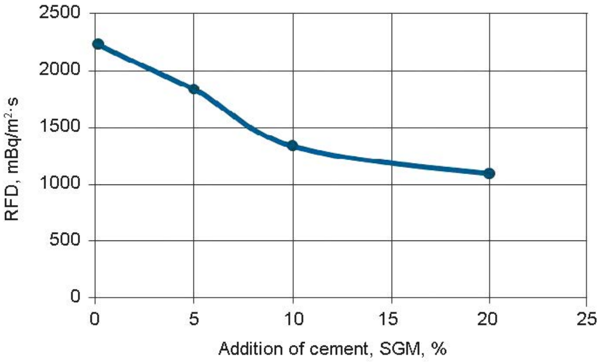


Figure 9. Changing radon flux density (RFD, mBq/m2·s) emitted by a paste based on materials from carbonate uranium ore processing depending on the amount of added cement (10%) and SGM (20%)

directly upstream the RW storage chamber. Additives are added to avoid cracking and shrinkage of the solidified paste in the chamber.

The quality of paste mixing and the distribution of additives throughout the volume of the mixer largely affects the strength of the paste filling during its solidification (Figure 8) [28].

The activity of materials from uranium ore processing is reduced in the presence of hardening additives. Radon releases occur from the near-surface layers of the paste filling from a depth of 6—8 cm; radon flux density (RFD) in a paste based on materials from aluminosilicate uranium ore processing amounts to up to 500 mBq/m^2·s; RFD in pastes based on finely ground materials from carbonate uranium ore processing amounts to up to 1,500—2,000 mBq/m^2·s [13, 14].

Addition of binders, reinforcing materials not only increases the strength of the paste filling, but also reduces the RFD. Figure 9 summarizes the findings of the PJSC PIMCU radiation safety laboratory on RFD decrease depending on the cement (10%) and sand- gravel mix (SGM) (5—20%) added to the paste [14].

Figure 9 demonstrates that the radon flux density is halved due to 20% SGM added.

Evaluated parameters of the paste backfill showed that this material may be used as an insulating shell fitted around RW containers designed for RW Class 2 and 3 in case of their chamber disposal. Special studies are required to assess the changing properties of the paste filling if these are held in chambers for long periods of time.

Consolidation of host rocks around RW storage chambers

Rock consolidation is a well-known process applied in underground ore mining. At the design stage, consolidation of fractured host rocks around the chambers is planned to be implemented in two stages. The first stage is the preliminary rope-injection hardening of the rocks constituting to the hanging, recumbent sides and roof (before ore breaking in the block takes place) providing for hardening composition injection through the wells into natural cracks and pores of tectonic and seismic origin.

The second stage provides for the consolidation of the chamber contours following ore extraction which seals some cracks evolving during the process operations. The walls are reinforced with a mesh and spray-concreting of the surface. When it comes to an already existing chamber with its walls previously not subjected to any strengthening, only the second stage is implemented.

Injection hardening of rocks can be anchor (to a depth of up to 5 m) or cable in its nature. Rock consolidation with cable injection rods is seen as a most effective method since these cables have the highest tensile strength and may be introduced into the well via narrow excavations due to transverse bending, while the cable rod length may amount to over 6—15 m. Figure 10 shows some types of cable rods [24].

The main element of the cable-injection rod is the carrier cable made of 7 twisted steel wires. The cross section of the rod is calculated based on the stresses acting on the cable in the rock mass: tension, tension and shear, pure shear, compression and shear.

W : C = 0.35—0.4 is considered an optimal water-cement ratio for a cement mortar. This ratio provides the highest compressive strength for the cement stone, as well as the highest elasticity modulus [24]. If a pre-tensioning option is considered under the cable-cement rod installation process, a polymer ampoule is first placed into the well, which is crushed by the edge of a cable in the bottomhole and hardens in a few minutes providing high intrinsic strength and adhesion to the cable and rocks.

High-strength non-shrinking concrete mixtures with different self-stressing energies and their initial viscosity being lower than the one of water were developed by the Parade Rus company (Smolensk).

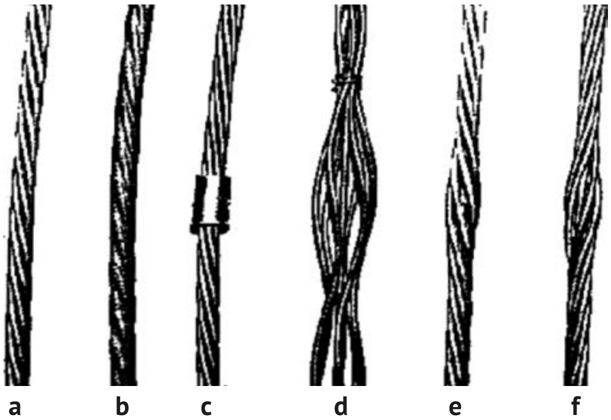


Figure 10. Types of cable rods: a — solid; b — with an epoxy envelope preventing corrosion under long-term operation conditions; c — with a steel clamp; d — with brace; e — with an insertable core; f - with a pear-shaped thickening

Polymer resins are widely used as rock hardening compositions, some of them are given in Table 4 [16].

Hardening compositions are fed through drilled holes or wells by high-pressure pumps into the fractured rock mass under high pressure (up to 15–20 MPa), thereby, existing cracks are filled with a composition that hardens providing high adhesion to the rocks.

The internal stress of a consolidated rock mass depends on the injection pressure and the properties of the hardening compositions applied, which are required to have adequate strength and shall be not prone to collapse under deformations and rock mass movements. Foaming polyurethanes (PPU 328, PPU 329 produced by JSC Polymersintez, Vladimir) penetrate into microcracks due to

Table 4. Polymeric materials produced in Russian and the properties of hardening compositions based on them

No	Resin type	Hardener	Dynamic viscosity, mPa·s	Gelation time, min	Resin-rock contact strength, MPa	
					for break	for shear
1	Epoxy	Amines	>400	3–40	20–50	35–65
2	Polyurethane PPU-328, PPU-329	Polyisocyanate grade B & D	230–350	3–45	3.0–45	4.0–45
3	Polyester	Benzene dioxide 8–10 %	200–350	3–50	2.0–12	3.0–14
4	Carbamide KF-BZh	Oxalic acid pp	140–230	5–300	2.7–2.9	2.9–3.3
5	KF-B	«	140–230	5–300	2.7–3.0	3.0–3.4
6	KF-Zh	«	140–230	5–300	2.5–3.0	2.7–3.2
7	KF-MT	«	140–230	3–100	3.2–3.8	3.6–4.1
8	Acrylic	Ammonium persulphates	150–250	10–50	0.8–2.5	1.0–2.5
9	Magnesia compositions	Magnesium chloride	200–250	15–300	0.5–5.5	0.7–5.8
10	Phenol-formaldehyde	Acids	180–280	5–200	2.0–3.5	2.4–3.8

molecular dispersion and additional pressure due to foaming, have elasticity and high strength, are least susceptible to deformation under rock mass movements, shaking due to blasting and natural seismic processes (Figure 11) [16].

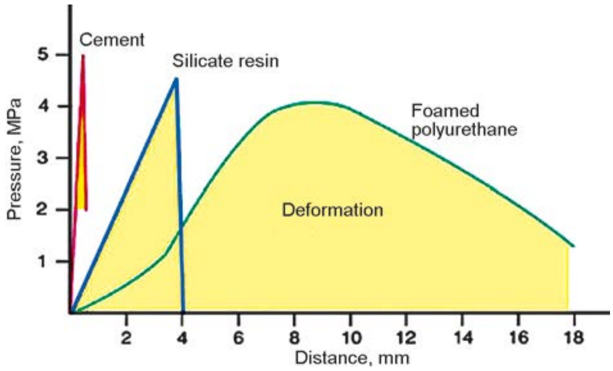


Figure 11. Comparison of strength (tensile) elastic properties of crack fillers during injection: cement, silicate resins, foaming polyurethanes

Parameters of fractured rock hardening

Several methods can be used to calculate the parameters associated with the cable-injection hardening of a fractured massif [18, 19] with one of them discussed below. Computational model involving some elements from the shell theory is based on the hardened zone represented by a pliable cable-stayed lining: blocks of immobilized hardened rock are strung tightly on the cables [18]. Condition providing for the hardened roof persistence can be represented as follows:

$$F_e = 0{,}125\, k_3 \rho h_n (L^2 + 4h^2)\, h,$$

where: F_e is the specific force pulling the cable out from the cement shell, kN/m; k_3 is the safety factor (equal to 1.5—2); ρ — average rock density producing a load on the hardened zone, kg/m^3; h_n is the height of the rock layer producing load on the hardened zone (in a simplified form it is the height of the rock cavity), m; L is the length of the cable in the excavation contours, m; h is the allowable vertical deformation of the roof, m.

The distance between adjacent cables is taken as the smallest of the below three depending on:

1) the tensile strength of the cable, $\sigma_{cab.t.}$, MPa:

$$\alpha < 1000\, \sigma_{cab.t.} S/(k_3 \rho h_n L),$$

where S is the area of the rock cavity along the cable axis, m^2;

2) the tensile shear strength of the rock mass (after its consolidation) $\tau_{s.sh}$, MPa:

$$\alpha < 2\tau_{s.sh} r L/(k_3 \rho h_n L \cdot 10^{-3} - 2\tau_{s.sh} r),$$

where r is the radius showing the distribution of reinforcing composition in the cracks of the rock mass;

3) the tensile strength in the upper part of the consolidated rock mass when the cement shell is punched by the cable $\sigma_{s.com}$, MPa:

$$\alpha < 1000\, \sigma_{s.com} d/(k_3 \rho h_n),$$

where d is the well diameter (cement shell), m.

The length of the locking parts of the cables should be no less than 1.5—2.5 m.

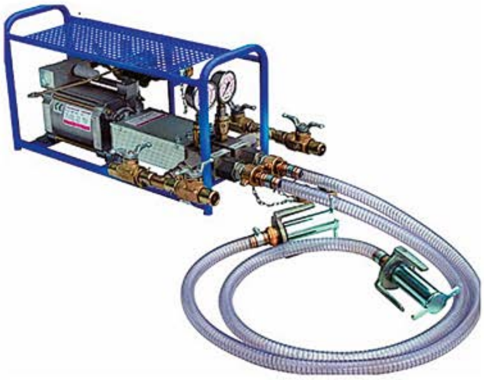
The calculated distance between the cables allowes to build a well drilling grid for the installation of cable injection rods. Their length and orientation can be calculated based on the orientation of the main fracture systems and the fracture zone dimensions.

Commonly, there are 5—9 systems of cracks intersecting a massif: under pressure, all of them are filled with a liquid composition. Therefore, when a reinforcing composition is injected, volumetric compression pressure acts on individual blocks and the entire rock mass in general. When their solidification is completed, the rock mass can be considered a monolithic conglomerate with high internal stress close to the equal component one. The strengthening quality, the crack filling completeness are checked by seismoacoustic methods of non-destructive testing [16].

At high discharge pressure, the stress-strain state of the rock mass (hereinafter referred to as SSS) suffers some dramatic changes: the reinforcing composition filling a crack space opens it with a force of up to 2,000 t/m^2, which is comparable to the weight of a 740 m high rock column (with an average volumetric weight of 2.7 t/m^3). The rock mass remains in a state of volumetric compression similar to structures made of prestressed reinforced concrete.

Solid rocks of the Antey deposit (Glubokiy mine) at a dept of over 500 m are prone to rock bumps — instantaneous transitions of the rock mass from the state of volumetric compression to the state of uniaxial compression with its simultaneous crushing. For example, the volumetric compression strength of gray sandstones amounts to 270 MPa (lateral compression of 80 MPa), whereas the uniaxial compression strength is equal to 160 MPa, i. e., is 1.7 times lower. Naturally, given a transition from the volumetric compression state to the uniaxial one (crack prompted by blasting) and providing that the remaining acting force exceeds the ultimate uniaxial compression strength, the free rock mass strip formed in the crack will be crushed [17].

This process and the subsequent one-by-one crushing of the resulting layers-surfaces occurs at



a

b

*Figure 12. Engineering methods used to strengthen the rocks with polyurethane resins:
a) S-35PU pneumatic two-plunger unit (Karbotech, Germany) providing the injection of one- and two-component compositions, pressure — up to 20 MPa, flow — 5 l/min, weight — 25 kg;
b) self-propelled unit Unigrout E-800-100WB (AtlasCopco, Sweden) providing the injection of hardening compounds into boreholes and wells with controlled supply and pressure*

a mechanical wave speed of 3.5—7.0 km/s, whereas the rock mass crushing occurs instantly, like an explosion.

A rock mass being in a compressive stress state, reinforced with cable-injection rods "binding" it in different directions is less prone to cracking, destruction due to blasting and other influences. Cable rods and hardening composition solidified in its cracks prevent the occurrence of rock bursts and their development.

Single- and multi-component cement slurries and polymer compositions can be pumped using numerous high-pressure pumping equipment produced both in Russia and abroad. When a decision is made on the application of particular pumps, one should consider the opportunities provided as regards the adjustment of composition supply (to opt for a laminar movement of the composition along the fractures), as well as the layout — in how many wells the composition is intended to be injected simultaneously and what injection pressure will be considered a threshold one for the hardened rock

Figure 13. DD 420 providing the installation of cable-injection rods designed by Sandvik (Sweden), capacity — 50 thousand m/year

mass (up to the hydraulic fracturing pressure). Figure 12 shows the equipment for hardening compound injection.

Figure 13 shows an example of a high-performance self-propelled machine for cable-injection rock hardening. The length of the outrigger-manipulator designed to install rods and to inject hardening compounds can reach 20 m. Robotic automation of such process as chamber prearrangement and multi-tiered container stacking are addressed by such companies as Vist, Epiroc, Sandvik, RCT, GHH Group and others.

Method providing the disposal of containers with RW Class 2 and 3 in abandoned chambers

For these purposes, a most stable chamber of a required size is either selected within an abandoned mine mothballed according to a dry method or in a remote isolated area of an operating mine. In the latter case, water inflow should be absent, it should be located in a return airway remotely from drilling, blasting and cleaning operations and should not interfere the underground transport. No abandoned chambers should be available below it with no mining operations neither performed nor planned. Hardening backfill with a non-shrinking additive should be to the extent possible filled into the adjacent chambers and the chambers above it. The decision made on the chamber selection shall be validated in relevant safety assessments.

The chamber is cleared of ore and rock by remotely controlled load-and-dump machines (RC LDM) with opportunities provided for their entering into the cleared space. Scaler is used to free the walls from balmstones. The bottom wall, if possible, is leveled according to a vertical position (Figure 14). Walls and roof are cleaned up and strengthened using cable-injection rods being of over 6—15 meters long with reinforcing compound injected into cracks, metal mesh and concrete sprayed on the chamber walls.

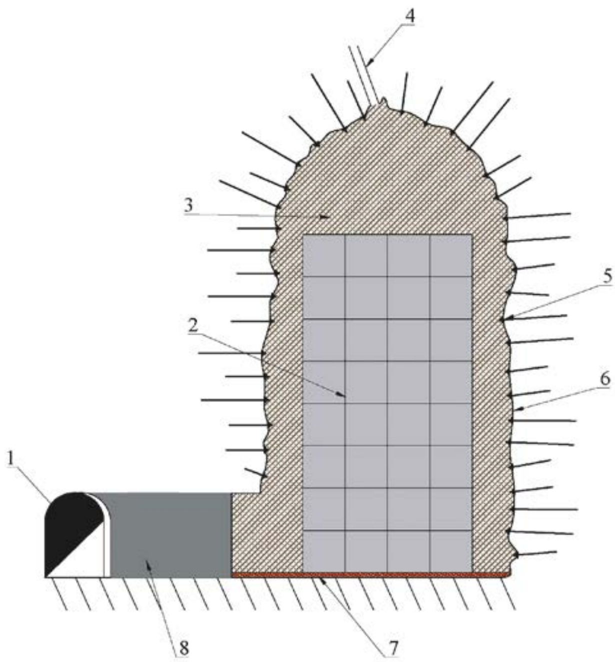


Figure 14. Disposal of containers with RW Class 2 and 3 in an abandoned chamber:
1 – drift, 2 – NZK 150-1.5P containers, 3 – paste filling,
4 – well used to supply the paste filling,
5 – cable injection rods, 6 – mesh and sprayed concrete,
7 – concrete base and bentonite layer, 8 – bulkhead

A ventilation system and a drainage system were installed along the chamber floor and in adjacent excavations preventing water seepage. A 0.5-meter-thick insulating layer of clay and bentonite, a layer of reinforced concrete with a thickness of 0.5 m or other thickness were installed on the chamber floor based on relevant assessments performed beforehand. A crane providing RW container handling operations and their stacking was mounted on the foundation arranged [20, 21].

The number of containers that can be installed along the length of a chamber depends on its dimensions and is validated in the safety assessments. Usually, the length of a chamber is 45—50 m. Given a lateral dimension of 1.7 × 1.7 m, up to 25 containers can be installed provided a 1.0—2.0 m wall gap required for crane legs. 4 containers can be emplaced into a chamber being 9—11 m wide (Figure 14). Given a chamber height of 15—17 m, containers can be potentially installed in 8 tiers. The capacity of a storage chamber of 50 × 11 × 17 m can be up to 800 containers with a volume of up to 1,200 m^3 RW (provided that the entire internal capacity of the containers is used).

After the containers are emplaced into a repository, video cameras are installed to monitor the level of void filling with paste, sensors are used to monitor the parameters of radioactive waste and paste backfill, seismic sensors check the solidity of the paste backfill and the enclosing rock mass. The crane, equipment and tools are removed, access crosscut and all excavations are plugged by high-strength concrete lintels with a thickness of over 8 m.

The paste filling is fed stage-by-stage in cautiously calculated portions through a well drilled in the upper part of the chamber roof, which is done to avoid extrusion of concrete lintels with unhardened paste at the access crosscut level. The initial viscosity allows the paste to fill not only the space between the containers and the walls of the chamber, but also between the containers in a stack and their tiers. The last portion is fed under pressure to fill the chamber "to the roof level". The hardening paste is considered not being prone to shrinkage or cracks.

After the chamber is filled, the monitoring system is switched to the long-term observation mode to monitor the parameters responsible for the repository state (solidity of the rock mass, radon flow density, activity, humidity, temperature, etc.).

Considering the high-responsibility level associated with the establishment of such facilities, safety assessment of such repositories and specific RW chambers intended for RW Class 2 and 3 disposal involving appropriate validation of the safety barriers and their parameters may be provided after relevant additives are selected, the properties of the paste backfill and the parameters of cable-injection host rock hardening method are tested. A number of laboratory-based and pilot tests are required to master the RW disposal method providing for RW Class 2 and 3 disposal in the underground space of uranium mines operated by PJSC PIMCU.

Conclusion

The paper considers a number of engineering technologies, namely, paste filling produced from uranium ore processing materials characterized with radiation resistance; cable-injection method applied to consolidate the host rocks around the chambers at great depths, including rock-bump hazardous ones; preliminary treatment of chambers preceding RW container emplacement; mining and geological rock characteristics of the Streltsovskoye uranium ore deposit based on which the safety assessment could be launched to demonstrate the prospects of using abandoned chambers constituting to underground mines run by PJSC PIMCU for the disposal of RW Class 2 and 3.

Availability of underground chambers suitable for RW disposal, as well as of ready-made surface and underground infrastructure (access roads, surface mine structures, vertical shafts equipped to provide personnel access, RW container transportation, transport excavations, ventilation systems, drainage systems, etc.) will decrease the repository construction costs.

Method providing for RW disposal in underground mines will fill its ecological niche in addressing the RW management problems. Once mastered, the method may help to expand the RWDF siting geography taking into account the needs of RW generators and provide some additional sites for reliable final disposal of such waste.

Further development and implementation of the method proposed for the disposal of Class 2 and 3 RW in the underground space of PIMCU mines requires field studies to be performed in a specialized laboratory. This research will help to develop methods that could be used to produce a paste with required parameters, to strengthen fractured rock masses, to emplace containers into chambers, to monitor the SSS of the environment in the mines [26], to monitor geodynamic, hydrodynamic parameters of the rock mass in the RW disposal area.

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