# METHOD FOR RADIOACTIVE WASTE DISPOSAL IN UNDERGROUND MINES

**Kuzmin E. V.[1], Kalakutsky A. V.[1], Morozov A. A.[2]**

[1]JSC Central Project and Technological Institute, Fuel Division of Rosatom TVEL, Moscow, Russia

[2]PJSC Priargunskoye Industrial Mining and Chemical Association named after E. P. Slavsky, Krasnokamensk, Zabaikalsky krai, Russia

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*This paper presents the key parameters associated with the disposal method used to dispose of radioactive waste (RW) of Class 2 and 3 in abandoned underground mines of PIMCU site assuming additional isolation of RW containers, adjustment of bedrock geomechanical properties and compliance with regulatory requirements. The paper briefly analyzes relevant international practices focused on RW disposal in natural and artificial underground cavities. It provides a comparison between the forecasted volumes of RW generation at the enterprises of the State Corporation Rosatom and the available underground disposal capacity at the PIMCU site. It presents the main characteristics of a paste filling manufactured based on materials from uranium ore processing and used as an insulating filler inside the vaults. The paper summarizes the results of operations on rock mass reinforcement based on injection method. It indicates the key advantages of the proposed method.*

**Keywords:** *radioactive waste, abandoned vaults, underground space, cable-injection rods, RW storage facility, bedrock reinforcement, paste filling, uranium ores, radon release, RW containers, RWDF construction.*

## Introduction

Relevance of the radioactive waste (RW) disposal challenge increases along with the growing RW amounts. To date, in uranium-producing countries, a total inventory of over 2.3 billion tones alone accounts for materials accumulated due to the hydrometallurgical processing of uranium ores. Therefore, considerations regarding the potential multifunctional use of subsoil, including the space of abandoned excavations and underground mines are becoming extremely popular [1, 2]. Decision-making regarding most effective and safest methods that can be applied to choose appropriate RW disposal options are made based on an integrated approach addressing the key interdisciplinary problems.

This study provides a new insight on the proposal regarding the potential of RW Class 2 and 3 (according to the accepted classification system [3]) disposal at great depths in the existing vaults of underground mines. Under this concept, RW containers are supposed to be isolated with a buffer paste filling produced from uranium ore processing materials (RW Class 6). Fractured host rocks are proposed to be treated to achieve a state of monolithic conglomerates, which is supposed to be done by means of injection hardening assuming that the fractures are sealed via the suppression of gas filtration processes.

The paper presents the main elements of a method proposed for RW Class 2 and 3 disposal assuming waste disposal in underground excavations resulted from ore mining. It's believed that this method can provide safe and reliable RW isolation within the abandoned space of uranium mines, reducing the repository construction cost by more than 60%. Particular case studies were considered to present the concept of container emplacement into the vaults and the calculated potential waste inventory at the PJSC PIMCU mines compared against the capacity required for the disposal of the entire RW inventory to be generated at the enterprises of the State Corporation Rosatom until 2025 and further on.

## Brief overview of the underground RW disposal practice

Nuclear power countries pay particular attention to the methods providing safe RW disposal. Geological RW disposal is seen as a method providing RW storage in a stable geological environment at a depth of 100—1,000 m. The option of deep geological RW disposal has been studied in many countries for several decades, which involved laboratory testing, geological analysis of promising sites, construction and operation of underground research laboratories. Table 1 presents some underground RW repositories and research laboratories available in nuclear power countries out of over 50 relevant facilities [4].

RW is disposed of in man-made and natural cavities supposing that the underground space is pre-filled with some solidifying solutions and the RW itself is fed through wells. Then the waste is backfilled with some buffer material and anti-filtration and waterproofing concentric cut-outs are installed around the disposal site [4, 5]. The capacity of such repositories is often small, they have quite complex structure, their construction requires extensive preparatory efforts with relevant financial and labor costs being quite high.

In Germany, a RW repository is being established for non-heat-generating low- and intermediate-level waste based on abandoned Konrad mine (Figure 1), which is a former iron ore mine [4, 6]. A 40 m thick ferrous limestone layer is located at a depth of several hundred meters and is overlaid by clayey rocks. There are two vertical shafts with a diameter of 7 m reaching a dept of 1,000 and 1,200 m that are supposed to provide personnel access, ventilation, rock lifting and transportation of RW packages.

Vaulted chambers intended for RW disposal are up to 1,000 m long, have a cross-section of up to 40 m$^2$ (height — 6 m, floor width — 7 m) and are associated with four horizons. The space around the RW packages (about 40 % of the excavation volume) stacked in three tiers is filled with a sorbent. The existing development excavations can be used to excavate some new vaults to reach a total capacity of about 1 million m$^3$ which corresponds to a disposal capacity required for the next 40 years of RW disposal assuming a reserve space of 50 %.

***Table 1. Underground RW repositories***

| Country | Name of the facility | Location | Disposed RW | Bedrock | RW disposal depth, m | Current state |
|---|---|---|---|---|---|---|
| Canada | NWMO DGR | Ontario | Spent nuclear fuel | Granite massif | 680 | Siting |
| Finland | ONKALO | Olkiluoto | Spent nuclear fuel | Granite massif | 400 | Construction |
| France | CIGEO | Bure | High-level and intermediate-level long-lived waste | Clays | ~500 | Siting |
| Germany | Morsleben | Saxony Anhalt | Low-level and intermediate-level waste | Salt massif | 630 | Closed in 1998 |
| Germany | Schacht Konrad | Lower Saxony | Low-level and intermediate-level waste | Sedimentary formation | 800 | Under development |
| Hungary | Bátaapáti | Bátaapáti | Low-level and intermediate-level waste | Granite massif | 250 | Operated |
| South Korea | Gyeongju | Gyeongju | Low-level and intermediate-level waste | Crystalline massif | 80 | Under construction |
| USA | WIPP | New Mexico | Transuranic waste | Salt massif | 655 | Operated since 1999 |
| USA | Yucca Mountain Project | Nevada | High-level waste | Volcanic rock massif | 200–300 | Under construction, 2010 – discussion |

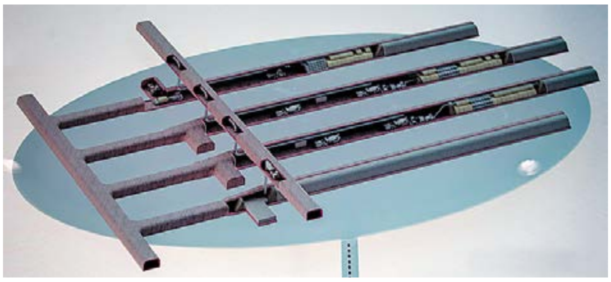

*Figure 1. Designs of an underground RW repository in the Konrad mine*

The Bataapati repository (Hungary) has a design capacity of 20,000 m$^3$ and is intended for low- and intermediate-level RW disposal. Its underground section is gridled with a transportation tunnel with dead-end disposal tunnels for RW emplacement. Arched disposal tunnels have a cross section of about 40 m$^2$ and a total length of 1,000 m (Figure 2) [4].

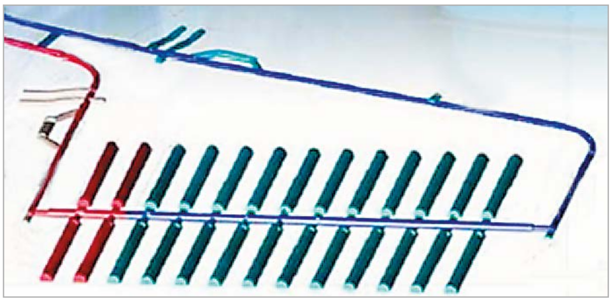

*Figure 2. The Bataapati repository*

The design capacity of the Yucca Mountain high-level waste repository planned for construction in the United States amounts to 77,000 tons and is proposed to be sited in a mountainous area at an average depth of 340 m from the surface (Figures 3a, b) [7]. Its construction was started in 1994. The main drift has the following characteristics: length — 7,900 m, diameter — 7.6 m, depth under the ridge surface — 300 m, height above the groundwater level — 200 m. In 2002, all studies (geological, hydrological, geochemical, geothermal, etc.) were completed and an application for an operational license was submitted to the US Nuclear Regulatory Commission. The site is located at a fault which entails some risks of water seepage. For this reason, the construction operations have been suspended.

In our country, the first disposal facility designed for solid RW of Class 3 and 4, which is a near-surface RW disposal facility, is located in the vicinity of the Novouralsk city. It has been operated since 2016. Two more RWDFs are being established as well: one repository with a design capacity of up to 200,000 m$^3$ is to be sited in the vicinity of the Ozersk city and the other one with a capacity of up to 150,000 m$^3$ — near the Seversk city. A deep RW disposal project is currently being implemented in the Russian Federation: the facility is planned to be sited within the Nizhnekanskiy massif (Krasnoyarsk Territory) in a monolithic block of Archean-Proterozoic granite-gneisses. This facility is designed to accommodate Class 1 and 2RW. An underground research laboratory (URL) is being created under the approved Strategy [8] on the disposal facility development [9, 10]. Decision regarding the repository construction is going to be made based on the URL research with relevant R&D activities to be started already at the excavation stage [11].

The above overview demonstrates that either a large salt or clay formation characterized with adequate plasticity and self-healing properties allowing to seal the fractures or a large monolithic block of crystalline rocks is being searched for during the repository sting process.  Granites, basalts, diorites, peridotites, etc. are characterized by long-term geochemical stability, high strength, relatively high thermal conductivity and low porosity.

This paper presents a different approach: already available vaults of underground mines located at great depths are proposed for RW Class 2 and 3 disposal. This disposal option also suggests that the containers are isolated by a shell made of a paste filling produced based on materials from uranium ore processing having high radiation resistance; whereas the fractured host rocks are upgraded to monolithic conglomerates by injection hardening.

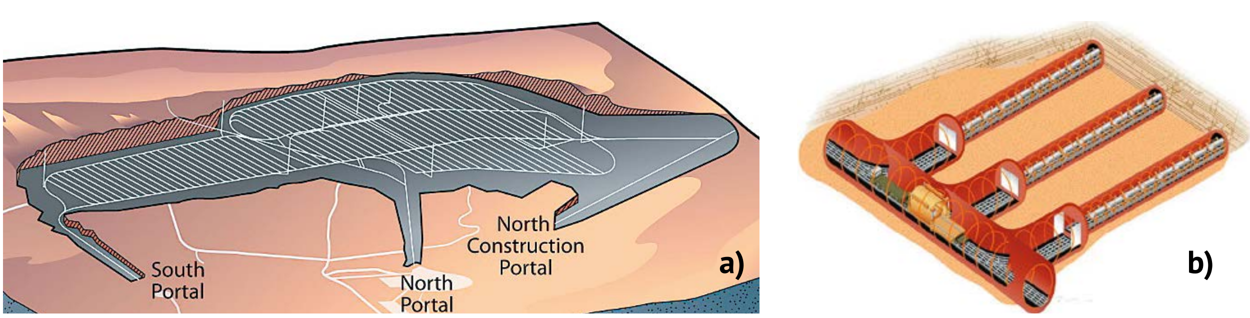


*Figure 3. The Yucca Mountain RW disposal facility: a) general layout of the repository, b) RW disposal tunnels*

## Compliance of conditions at the PJSC PIMCU site with regulatory RWDF siting requirements

Decision-making regarding the RW disposal method, structure designs, structure and properties of safety barriers is done based on the characteristics of RW planned for disposal in the considered facility, the waste inventory, environmental setup within the siting area and relevant safety assessments. In accordance with the national regulatory requirements (NP-055-14):

- RW Class 1 and 2 should be disposed of in deep RWDF;
- RW Class 3 and 4 should be disposed of in near-surface RWDF, i. e., structures located either above the ground surface level, at the same level with the ground surface or below the surface at a depth of up to 100 m.

RWDF shall not be sited directly on active faults or within active geodynamic zones. Faults are present at the sites of mine No. 1 and mine Glubokiy: Streltsovskiy fault, Vostochnaya zone, Central zone, Malo-Tulukuevskaya zone formed in the Paleozoic, Mesozoic and Cretaceous periods some 100 million years ago and earlier. The above faults are not listed as active faults according to the Geological Institute of the Russian Academy of Sciences [12]. As regards the Glubokiy mine, parameters of the local rock mass, which is characterized by heterogeneity of the stress-strain state should be studied and analyzed during relevant repository siting activities [13—16].

RW repositories should not be sited in areas with a seismicity level being equal to the intensity of the maximum design earthquake exceeding 8 points according to the MSK-64 scale. According to the OSR-2016-D map (General Seismic Zoning of the Territory of the Russian Federation), mines No. 1 and Glubokiy are located in the areas with a maximum earthquake intensity of 7 points. The recurrence period amounts to 1,000 years. Therefore, within 50 years, the calculated intensity can be exceeded with a probability of some 0.5 %.

The proposed underground mine disposal option for RW Class 2 and 3 suggesting the use of underground excavations and vaults of uranium mines assumes that a system of four isolating barriers is established:

1) **containers** — the main insulating barriers made of metal or reinforced concrete;
2) **paste filling** the voids between the walls of the vaults and containers which is made of materials from uranium ore processing (RW Class 6) characterized with adequate radiation resistance due to the radioactive elements available in them;
3) **injection hardening of rocks** constituting to the walls and roof of the vaults using hardening compounds;
4) **disposal depth of over 1,000 m:** a thick massif of overlying rocks composed of granites, felsites, conglomerates, gravelites, trachydacites, basalts.

This paper consistently explores the characteristics of these insulating barriers (except for the $4^{th}$ barrier).

The use of fiber-reinforced concrete NZK-150-1.5P containers (1.65 × 1.65 × 1.375 m) with a useful capacity of 0.8 $m^3$ is considered as an option under the underground mine RW disposal concept [17]. It appears to be a preferrable option in terms of RW isolation. The surface of concrete structures is potentially subject to a degradation at a rate of some 10 cm per 1,000 years. Based on the simulation of concrete layer degradation, the destruction rate has accounted for 6 mm per 300 years (Figure 4) [19].


*Figure 4. Fiber concrete NZK-150-1.5P container for RW disposal: a) general view, b) internal space involving 4 RW packages with a total capacity of 0.8 $m^3$*

## Volumes of RW generation at the enterprises of the State Corporation Rosatom

The volume of previously accumulated Class 3 RW amounts to some 900,000 $m^3$ (considering the container capacity). Table 2 presents the forecasted Class 1—6 RW inventory that is to be generated by the enterprises of the State Corporation Rosatom in the next 15 years [18]

***Table 2. Forecasted inventory of RW generation by the enterprises of the State Corporation Rosatom***

| RW class | Until 2025, $m^3$ | Until 2035, $m^3$ |
|---|---|---|
| 1 | 3,050 | 5,450 |
| 2 | 48,154 | 80,154 |
| 3 | 230,508 | 304,111 |
| 4 | 535,942 | 1,208,282 |
| 5 | 13,039,387 | 21,531,007 |
| 6* | 18,815,500 | 30,175,500 |

* from the mining and milling of uranium ores, mineral and organic raw materials with an increased content of natural radionuclides.

*Table 3. Volumes of voids in operating and mothballed PJSC PIMCU mines*

| Developed systems | Abandoned mines, thousand m$^3$ | | Operating mines, thousand m$^3$ | | |
|---|---|---|---|---|---|
| | Mine № 2 | Mine № 4 | Mine № 1 | Mine № 8 | Mine Glubokiy |
| Backfilled horizontal layers | 460.16 | 117.12 | 1,374.91 | 286.4 | 560.19 |
| Vault systems | 206.51 | 37.07 | 326.55 | 2.79 | 1,486.58 |
| Total void volume | 666.67 | 364.22 | 1,701.46 | 613.94 | 2,326.34 |

## Availability of underground space at the PJSC PIMCU mines

At PJSC PIMCU mines, the ore bodies are mainly mined using vaulted mining systems, layered systems with descending and ascending excavation. Table 3 presents the capacities of excavated not backfilled mine space at operating and abandoned PIMCU mines as of September 2018 [19].

The exhausted capacity at mines No. 1 and Glubokiy amounts to over 1.5 million m$^3$, which can cover the entire needs (about 280,000 m$^3$) of the State Corporation Rosatom for the disposal of the forecasted RW Class 2 and 3 inventory taking into account the existing restrictions.

Moreover, vaults with a total capacity of up to 250—300 thousand cubic meters will be excavated annually at the mine No. 6 currently being under construction. According to the geological exploration data of the Argun deposit, most of the reserves are represented by ore bodies with a steep dip ranging from 55° to 85° having a thickness of up to 45 m [20]. Abandoned vaults can be also considered as potential sites for RW disposal during the preliminary analysis of influencing factors and at the preliminary stage.

## Paste filling based on uranium ore processing materials

In the underground vaults, the space between a pile with RW containers and the walls is supposed to be backfilled with a paste filling made from uranium ore processing materials with the addition of flocculants, binders and inert additives (cement, fly ash, sand and gravel mixture, crushed rock).

JSC VNIPIpromtechnologii and PJSC PIMCU have been studying the properties of such paste filling [21, 22], which is a gel-like mineral mass with a density of up to 1.2—1.8 t/m$^3$ that chemically reacts neither with metal nor with concrete containers and is not flammable since it consists of crushed materials from uranium ore processing, water and mineral additives (Figure 5).

Depending on the additives and fillers, the paste filling gains a compressive strength of over 1.0—2.0 MPa within 30—60 days.

## Fractured host rock hardening

Rock hardening with wireline-injection rods is considered as a most effective method out of several methods providing the fractured rock mass hardening, since the fastening can be installed from narrow excavations, while the length of the rod can be 6—15 m due to the transverse cable bending; the cable can withstand higher tensile loads as compared to other types of roof bolting; applied reinforcing compounds (microcements, geocements, polymer resins) are considered as generally available materials.

Injection rock hardening method was studied at the Moscow State Mining University [23]. According to this method, the strengthening compounds are fed into the fractured rock through boreholes or wells using high-pressure pumps (building up a

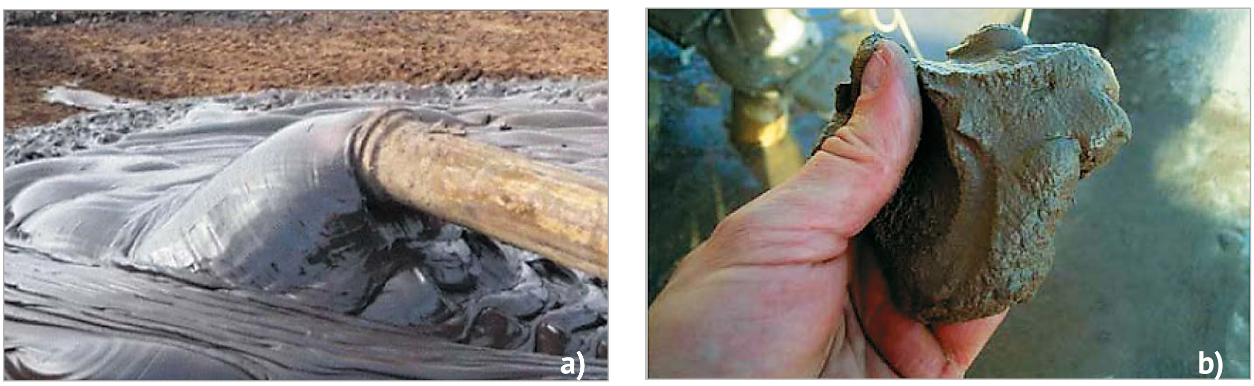

*Figure 5. Paste filling based on uranium ore processing materials: a) supply through a pipeline, b) deep thickening paste*

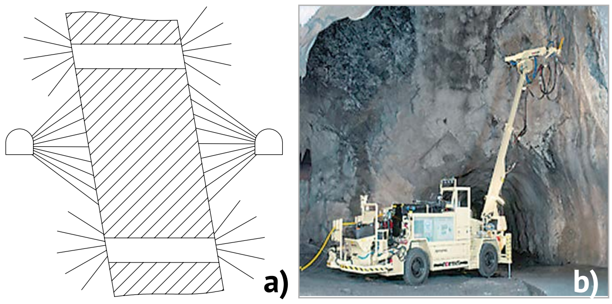


*Figure 6. Rod injection hardening of the bedrock:*
*a) preliminary hardening,*
*b) subsequent hardening after vault exhaustion*

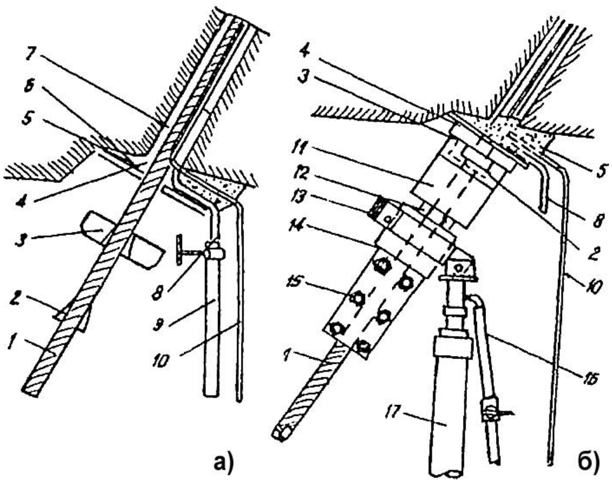


*Figure 7. Cable tension: a) injection rod design,*
*b) cable tension device:*
*1 — cable; 2 — conical wedge; 3 — spacer plate;*
*4 — bearing plate; 5 — cement mortar; 6 — burlap; 7 — paper;*
*8 — tube for solution supply; 9 — hose to the cement pump;*
*10 — a tube for air release; 11 — hydraulic jack;*
*12 — pump plunger; 13 — clamp; 14 — tension jack;*
*15 — clamping bolt; 16 — air hose; 17 — pneumatic support*

pressure of up to 15—20 MPa) filling up the available open cracks (Figures 6, 7). Taking into account the heterogeneity of the stress-strain state, various disturbances in the rocks available at different horizons of the Glubokiy mine and different fracture systems, the massif can be passed through twice using cross-boreholes or wells to inject the filling composition providing the filling of almost all existing cracks.

In a fractured medium, rock pressure forces are transferred through rock interfaces along which the adjacent blocks of the rock mass come in contact with each other. According to professor K. V. Ruppeyt, the area of rock interfaces (the ratio between the interface area and the total area of the crack) accounts for (3—4)·$10^{-3}$ [24]. Therefore, the surface of the cracks is basically open. Usually, the ore deposit rock mass involves from 5 to 9 intersecting fracture systems. Upon the solidification of the hardening composition in cracks, the massif, being under pressure, becomes a monolithic conglomerate with high internal stress, similar to building structures made of prestressed reinforced concrete.

The hardening quality, the completeness of crack filling and the solidity of the massif are evaluated by seismoacoustic methods of non-destructive testing [23].

Different fracture systems are available at different horizons within the rock mass of the Antey deposit (Glubokiy mine) affecting its mechanical stability. Upon being injected into the rocks, the hardening compound penetrates the cracks providing some opening and exerts a pressure perpendicular to the crack surface, pressing the existing inclusions. This mechanism is provided by high injection pressure making the composition to penetrate the fractures with maximum laminar velocity, but not causing the hydraulic fracturing of the cracks.

Starting from a depth of 500 m, east of seam 160, the rocks of the Antey deposit are considered prone to rock bursts occurring due to massif transition from the volumetric compression state to the uniaxial one assuming a setup when one of the remaining acting forces exceeds the ultimate strength by uniaxial compression. In the case of injection rock hardening, the cracks are filled with a hardening composition acting on the massif compression in all directions with a pressure comparable to the weight of the overlying rocks, which levels up and restores the bulk stress state of the massif making it akin to an equal component state. The likelihood of rock bursts reduces significantly [27]. In addition, massive explosions were done in the abandoned vaults during ore mining to reduce the stresses in the rock mass, to level the stress-strain rate and to reduce the risk of rock bursts. Therefore, most of the abandoned vaults can be considered acceptable for RW disposal purposes.

## Key parameters of the underground mine disposal option for RW Class 2 and 3

The proposed method assumes the disposal of solid non-heat-generating RW of Class 2 and 3 suggesting that the waste in metal or reinforced concrete containers is emplaced into abandoned vaults and the rock insulation is provided by a lining made of a hardening paste filling based on uranium ore processing materials [25, 26]. To suppress the hydro-gas filtration processes, wire-injection hardening of the solid host rock mass is applied to seal the existing man-made and natural cracks. The thickness of the hardened rock zone around a vault can range from 5 to 20 m depending on the rock mass fracturing.

Containers with RW Class 2 and 3 (not-heat generating RW) can be disposed of in underground excavations and vaults according to the below options:

- using the free space of abandoned extraction vaults at existing and abandoned mines;
- using long excavations of a small cross-section.

### Disposal of RW containers in abandoned vaults

A vault not interfering with the underground transport and being located remotely from drilling and blasting operations is selected. Then its walls and roof are cleaned out and strengthened using injection rods with a sprayed concrete metal grill. A drainage system is installed along its floor and in the adjacent excavations preventing water inflow into the vault. A ventilation system is installed as well. A 0.5 m thick layer of reinforced concrete and an insulating 0.5 m thick layer of bentonite are installed on the floor of the vault with RW containers being placed on this foundation [25, 26].

The containers are placed along the length of the chamber with their number being consistent with the vault capacity. In a 50 m long vault, 25 containers can be installed with their dimensions in the plan accounting for 1.7 × 1.7 m considering a gap size to the walls of 1.0—2.0 m. In a vault being 11 m wide, 4 containers can be installed (Figure 8). Considering a vault height of 15—17 m, containers can be installed in 8 tiers. 800 containers with a capacity of 640 m$^3$ can be accommodated within a storage vault of 50 × 11 × 17 m. Considering a gap of 1 m, a total of 1,080 containers with a capacity of 864 m$^3$ can be accommodated within a vault.

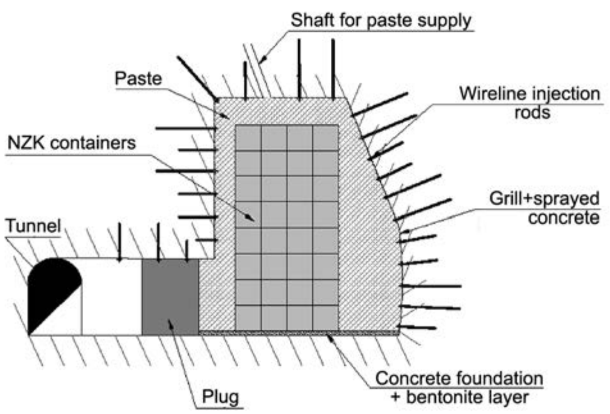


*Figure 8. Disposal of NZK-150-1.5P containers with RW Class 2 and 3 in a vault with voids backfilled with a paste*

When the container disposal operations are completed, the equipment and machines are removed from it, the ort-drives and all auxiliary excavation are sealed with reinforced concrete plugs being of over 8 m long. The paste filling is supplied through a well in the roof, which is done according to strictly defined stages until the vault is completely filled with paste. Cameras installed at different levels and sensors pre-installed on the containers are used to monitor the backfilling process, the container state and paste supply. With time this process transforms into a long-term monitoring of storage conditions (radon flux density, activity, humidity, temperature, etc.).

A total of 438 storage vaults with the above capacity will be required to dispose of the Class 2 and 3 RW inventory that is going to be generated in the Russian Federation by Rosatom enterprises by 2025 (280 thousand m$^3$).

Vaults of a greater width (length 45—50 m, width 17 m, height 16—18 m) can accommodate 25 containers lengthwise, 8 containers in width and 8 tiers in height (Figure 9). The same methods are going to be applied to arrange for the drainage and ventilation systems, to concrete the floor of the vaults, to install containers in tiers, to fill the cavities with the paste filling, to isolate the bulkheads, to provide the operation of the monitoring systems. The total number of containers in a 50 × 17 × 16 m vault will amount to 1,600 pieces allowing to accommodate a total of 1,280 m$^3$ of radioactive waste. Therefore, to accommodate the entire inventory of RW Class 2 and 3 expected to be generated in the Russian Federation by the enterprises of State Corporation Rosatom by 2025, a total of 219 storage vaults with the above capacity are going to be required. During the decision-making process, the preference should be given to wide vaults.

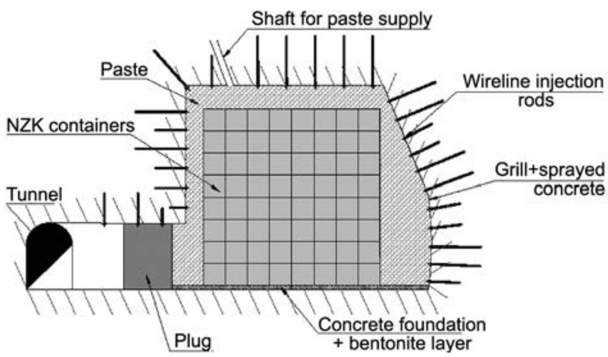


*Figure 9. Disposal of NZK-150-1.5P containers with RW Class 2 and 3 in a wide vault*

### The use of long excavation of a small cross-section

A large number of long excavations with a cross section of 13—20 m$^2$ is available in the mines. As regards the mining waste in case of layered excavation, the volume of rocks excavated at the preliminary stage accounts for more than 40 % from the total volume of the excavated rock mass. In the selected area, wireline reinforcement of roof and wall rocks is applied involving a grill and sprayed concrete or a sprayed polymer composition with high insulating properties (for example, 5—8 mm thick TSL 865 geomembranes from BASF, Figure 10) [28]. A 0.5 m thick bentonite layer is applied to the soil of the excavation. After the RW container installation is completed, the mine is insulated with concrete plugs and backfilled with a paste filling supplied through a special well. The excavation backfilling process, as well as the further state of the RW should be monitored (as discussed above).

*Figure 10. Application of a polymeric geomembrane to the surface of a mine excavation after wireline-injection hardening of the sides and roof rocks, grill installation, before RW container installation and backfilling with a paste filling*

Considering the critical importance of efforts associated with the RW storage vault operation and those implemented beforehand, as well as the requirements regarding the long-term safety, the safety assessment considering some particular vaults and involving the safety demonstration of EBS (engineered barrier system) parameters can be presented following the paste backfill testing, the identification of optimal geological properties, required strength level that can be adjusted using additives and neutral fillers. Parameters of the fractured host rock injection hardening should be studied accounting for different fracture systems of various origin. To master the method proposed for the underground mine disposal of RW Class 2 and 3 in PJSC PIMCU uranium mines, staged laboratory and pilot testing is required. Table 4 presents a list of key steps required to prepare the vaults for the disposal of RW Class 2 and 3 that should be taken into account to draw up a target business model, top-level charts and financial and economic models associated with the project. Table 5 presents the cost indicators for the construction of a near-surface RWDF and a deep RW repository of an underground mine type.

The profitable part of the project seems to be very attractive, taking into account the tariffs (for 2020) for RW Class 2 disposal — 729,256.92 rubles/m$^3$, RW Class 3 disposal — 168,070.83 rubles/m$^3$ (excluding VAT).

***Table 4. List of key operations to prepare a vault for RW disposal***

| № | Operations |
|---|---|
| 1 | Vault preparation for waste acceptance: strengthening the walls and roof with wireline-injection rods, grill with sprayed concrete, drilling of paste supply wells, erecting a reinforced concrete foundation, installation of a waterproofing bentonite layer |
| 2 | Container delivery to a temporary storage facility, delivery of containers to the mine shaft |
| 3 | Loading, container lowering in cages to deliver them to the disposal horizon, unloading, electric locomotive haulage on platform trolleys |
| 4 | Unloading, tire-wise installation of containers inside the storage vault, installation of sensors to monitor the state of RW containers and paste filling |
| 5 | Installation of concrete plugs in delivery and sublevel excavations |
| 6 | Staged chamber backfilling with a paste insert to avoid the installed plug squeezing out, checking the completeness of the backfilling operation |
| 7 | Radiation monitoring, monitoring of radon emission, humidity, monitoring the container temperature, testing the solidity of the enclosing rocks by seismoacoustic non-destructive methods, etc |

*Table 5. Comparing the costs of RW Class 2 and 3 disposal in a near-surface RWDF vs. an abandoned underground mined vault [18]*

| Name of cost items | The cost structure for the disposal of RW Class 2 and 3 | |
|---|---|---|
| | In a near-surface disposal | In abandoned chambers at great depth |
| Loading and closing RWDF modules | 1,853.27 | – |
| Operation of key systems | 5,001.79 | – |
| Pre-design stages | 12.96 | 13.00 |
| Prospecting | 102.32 | 102.32 |
| Design | 214.32 | 214.32 |
| Surface infrastructure | 1,081.26 | 1,050.00 |
| Preparation of the area | 447.03 | – |
| Preparation of the receiving area | – | 100.00 |
| Construction of RWDF modules | 2,880.18 | – |
| Complex for paste filling production | – | 1,000.0 |
| Pre-backfilling and backfilling of the vaults | – | 1,400.00 |
| Monitoring and control | – | 600.00 |
| Total | 11,593.13 | 4,479.64 |

## Conclusion

The paper proposes a method for RW Class 2 and 3 disposal in abandoned vaults of the underground PJSC PIMCU mines suggesting the installation of insulating barriers, including paste filling fabricated based on materials from uranium ore processing and forming a shell around the container stacks. This method also provides for the injection bedrock hardening, namely, of the storage vault walls and roofs which is done via the application of hardening compositions with the fractured enclosing rocks being upgraded to monolithic ones.

This disposal method is characterized by the following advantages:

- no need to build a new RWDF, there is a ready-available underground vault space with a capacity of up to 1.5 million m$^3$;
- the construction cost of a near-surface RWDF is 2.6 times (by 7.04 billion rubles) lower than the cost of a deep RW repository;
- business diversification: it launches a large highly profitable line of PJSC PIMCU production activities providing the disposal of RW Class 2 and 3 in the underground mines and new employment opportunities;
- multi-staged isolation provides reliable and safe disposal of three RW classes: Class 2, 3 and 6;
- containers with intermediate-level waste are isolated with paste, i. e., low-level waste, which, in turn, are isolated by the injection hardening of the enclosing rocks;
- PJSC PIMCU payments for the surface storage of materials generated from the uranium ore processing are reduced (by 160—220 million rubles/year);
- the safety of RW Class 2 and 3 long-term deep storage increases while reducing the risks of inadvertent intrusion and the possibility of terrorist acts.

In addition to the abandoned PJSC PIMCU mine vaults, there is a readily-available surface and underground infrastructure required for RW container reception, transportation and disposal:

- access roads, railway communication service, surface intermediate storage sites, warehouses;
- supply of power lines, transformer substations;
- vertical shafts reaching a depth of over 1,000 m with cage lifts for personnel access and RW container transport;
- equipped shaft pockets, transport excavations along the horizons, electric haulage tracks, platform trolleys;
- drainage system, forced central and local ventilation systems, etc.

Possible RW container layout has been presented: 800 containers with a capacity of 640 m$^3$ can be accommodated in a 50 × 10 × 15 m storage vaults. A total of 438 storage vaults with the above capacity will be required to accommodate the entire inventory of RW Class 2 and 3 to be generated by the enterprises of the State Corporation Rosatom by 2025.

The number of containers in a 50 × 17 × 16 m vault will amount to 1,600 pcs: these will be able to accommodate 1,280 $m^3$ of radioactive waste. The total number of storage vaults having the above capacity required to accommodate the entire RW Class 2 and 3 inventory to be generated by the enterprises of the State Corporation Rosatom by 2025 will amount to 219 pcs.

The total capacity of abandoned PJSC PIMCU mine vaults amounts to over 1.5 million $m^3$, which can largely satisfy the needs of the Rosatom State Corporation in terms of the required disposal capacity for RW Class 2 and 3 providing no opportunities for RW retrieval in the future.

To further explore the opportunities of RW Class 2 and 3 disposal in the underground space of PJSC PIMCU mines, a specialized subdivision (a special underground laboratory for innovative technologies [29, 30]) should be established to monitor the SSS environment at mines, to finetune the RW disposal method, to monitoring the fulfillment of safety requirements, the parameters of the storage facilities, geodynamic, hydrodynamic parameters of the rock mass at the disposal site.

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## Information about the authors

*Kuzmin Evgeny Viktorovich,* Doctor of Science, professor, Chief Expert, JSC "Central Project and Technological Institut", Fuel Division of Rosatom "TVEL" (49/74, Kashirskoje Road, Moscow, 115409, Russia), e-mail: Eugen.kuzmin2017@yandex.ru.

*Kalakutsky Aleksey Vasilyevich,* PhD, Head of the Research and Innovation Department, JSC "Central Project and Technological Institut", Fuel Division of Rosatom "TVEL" (49/74, Kashirskoje Road, Moscow 115409, Russia), e-mail: alvkalakutsky@rosatom.ru.

*Morozov Aleksandr Anatolyevich,* PhD, Director of Science and Innovation Development, PJSC "Priargunskoye Industrial Mining and Chemical Association named after E. P. Slavsky" (11, Stroiteley Ave, Zabaikalsky krai, Krasnokamensk, 674673, Russia), e-mail: morozovaa@ppgho.ru.

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