DURABILITY OF REINFORCED CONCRETE CONTAINERS NZK-150-1.5 P DURING THE DISPOSAL OF RADIOACTIVE WASTE CLASS 2

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The article focuses on experimental, calculation and analytical basis demonstrating the durability of reinforced concrete NZK-150-1.5P containers designed for the deep disposal of intermediate long-lived class 2 radioactive waste in the Nizhnekanskiy rock mass (DDFRW NKM) and the associated challenges. The article shows that the regulatory framework should be updated to reduce the requirements specifying the time during which the packages have to maintain their protective properties in case of intermediate-level waste class 2 disposal.

Keywords: *radioactive waste, reinforced concrete container, durability, disposal, deep disposal facility.*

Introduction

According to the Federal Law On Radioactive Waste Management and Amendments to Certain Legislative Acts of the Russian Federation No. 190-FZ of July 11, 2011, all removable RW shall be processed and conditioned, i.e., the resulting waste form shall comply with the acceptance criteria for disposal.

The following container types are most widely used to package conditioned low- and intermediate-level waste Class 3 and 4: metal KRAD, KMZ- type containers and reinforced concrete NZK-type containers of various designs. Nevertheless, no package designs are currently available for conditioned RW Class 1 and 2 that could meet relevant regulatory requirements for the required service life of 1,000 years.

The most urgent challenge is seen in the development of container designs for intermediate-level long-lived waste Class 2, which include: metal waste, spent graphite from uranium-graphite reactors, cemented LRW from radiochemical production facilities, etc.

Metal container designs proposed for conditioned RW Class 2 packaging and disposal have not been subject to a sufficiently detailed scientific or feasibility study.

Reinforced concrete non-returnable containers NZK-150-1.5P manufactured according to L65.555.00.00.000 specification with improved designs meeting modern regulatory requirements can be proposed as an alternative packaging option for conditioned long-lived intermediate-level waste Class 2.

Brief overview summarizing the research on the durability of concrete and reinforced concrete

In the world practice, no regulations are in place setting forth the requirements for the service life assessment of reinforced concrete structures covering a period of over 100 years, which can be explained by relatively short time elapsed since the development of modern concrete and reinforced concrete designs (about 180 years) and the variety of operating conditions assumed for such structures.

The required service life of such engineered structures (up to 100 years) is set forth by the following Russian regulations:

- SP 28.13330.2017 Code of Rules. Protection of Building Structures Against Corrosion;
- SP 35.13330.2011 Code of Rules. Bridges and Pipes. Ed. 2017;
- SP 58.13330.2012 Hydraulic Structures;
- SP 120.13330.2012 Subways. Ed. 2017;
- SP 122.13330.2012 Railway and Road Tunnels. Ed. 2017.

Taking into account the operating experience of the listed facilities, the above regulations assume that by the age of a hundred years or earlier, these facilities will basically become obsolete, won't be able to meet the new operating conditions and will be subject either to some upgrading or demolition.

Similar provisions regarding service life assessment and its assignment are applied to buildings and structures in other developed countries as well.

The service life of concrete and reinforced concrete has been studied continuously since its inception. A few publications [1]—[16] provide the information necessary to assess the durability of the structural material constituting to the reinforced concrete container NZK-150-1.5P. This container design was proposed for ILW Class 2 packaging assuming its subsequent disposal.

It has long been established that under different operational conditions referred to as environmental aggressivity, the durability of concrete and reinforced concrete varies greatly — from several years to several centuries [1].

Literature sources provide numerous case studies considering structures made of a concrete type material that withstood thousands years of operation. Some cases in point to note with the concrete structures still remaining in good condition after over 1,000 years of operation are maritime structures in Rome, the dome of the Roman Pantheon [2].

On a global scale, concrete has become a widely used material and its quality indicators (strength, durability) have increased many times over almost two hundred years elapsed since its invention.

Thus, in 1960, the highest strength of concrete was 40 MPa, in 1970 it amounted to 50 MPa, in 1980 — to 70 MPa, in 1990 — to 100 MPa, in 1995 — to 200 MPa [11]. High-strength concrete and reinforced concrete are used to build unique structures designed to operate for over one century. For example, the Ostankino television tower being 537 m high was erected in Moscow in 1963—1967. Its reinforced concrete part reaches a height of 380 m. In 1976, construction of a 79-storey building was completed in the US. In Malaysia, two towers of over 100 floors made of grade B80 concrete were erected. In the North Sea in 1995, Norwegian engineers installed a 472-meter-high oil production platform located in the area with a sea depth of over 300 m. In Canada, the Anasis Bridge with a central span of 465 m was commissioned in 1986. In Europe, cable-stayed bridge with a span of 864 m was commissioned in 1998. The same year saw commissioning of a cable-stayed bridge Vasco da Gama with its central span of 890 m in Lisbon [11]. Thus, there are multiple examples of this kind that can be mentioned.

The durability of reinforced concrete products and structures of only up to 100 years was conclusively established in regulations, although the practice of their application in unique structures requires trouble-free operation for longer periods.

Numerous papers exploring the behavior of reinforced concrete structures and the opportunities for increasing their resistance (safety) in aggressive environments have been published to date. In the vast majority of cases, the durability of reinforced concrete is considered assuming some specific operating conditions, and its assessment is usually descriptive in its nature and is rarely evaluated based on some analytical formulas.

In [4], the author proposes to evaluate the durability (service life) of concrete based on expression (1), which includes the following empirical coefficients:

$$D = D1 \cdot K1 \cdot K2 \cdot K3 \cdot K4 \cdot K5 \cdot K6 \cdot K7, \qquad (1)$$

where D1 is the standard durability of concrete, 60 ears;

K1 stands for the cement quality factor ranging from 0.5 to 1.8:

K1 = 1.8 — for belite Portland cement with a specific surface area of up to 3,000 cm^2/g;

K1 = 0.5 — for finely ground high-aluminate Portland cement with inert and active mineral additives;

K2 = (1.2—0.7) reflects the quality and uniformity of raw materials;

K3 = (1.2—0.7) reflects the quality of the concrete mixture production process;

K4 = (1.1—0.8) reflects the conditions for mixture transportation and its emplacement into the structure;

K5 = (1.2—0.6) indicates concrete hardening conditions;
K6 = (1.1—0.9) indicates the quality of concrete maintenance while the structure is hardening;
K7 = (1.1—0.9) indicates the uniformity of concrete and the mode of structure operation.

Taking into account all the conditions along the upper margin, which are typical for concrete Class B50 and Grades F500 and W10-W16 according to the frost and water resistance levels respectively, the durability of reinforced concrete can amount to 270 years.

The empirical formula (2), similar in its structure to the one described above and given in the same paper, was proposed in Japan [4]:

$$Y = Y1 \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \cdot H, \qquad (2)$$

where Y1 is the standard durability of concrete, 60 years;
A is the concrete type coefficient: A = 1.0 — for ordinary heavy concrete and A = 0.85 — for light concrete;
B is the cement type: B = 1.0 for Portland cement and B = 0.85 for Portland slag cement;
C is the water-cement ratio:
C = 1.0 — for W/C = 0.65 and C = 1.5 — for W/C = 0.55;
D is the thickness of the protective reinforcement layer: D = 1.0 — a protective layer of 40 mm, D = 1.56 — of 50 mm and D = 0.25 — of 20 mm;
E — type of lining (surface protection): E = 0.65 — without lining, E = 1.5 — lining with mortar and E = 3.0 — lining with tiles;
F — construction method: F = 1.0 — normal, F = 1.5 — high quality;
G — operating conditions: G = 1.0 — during routine repair of defects and degradation spots;
H — external operating conditions: H = 1.0 — normal, H = 0.9 — cold, H = 0.8 — coastal.

If we assume the following coefficients C = 2.5 (W/C = 0.35), D = 1.0 (concrete belongs to the category of especially dense materials), E = 1.5 (concrete is especially dense and does not require mortar lining), and the rest — according to the upper limit, i. e., the coefficients would meet the requirements for materials and methods applied in the production of high-quality concrete, then its durability amounts to 300 years.

It should be noted that the Japanese approach to life evaluation refers to ordinary bulk concrete with no account taken of the strength increase over time, which positively affects the durability of reinforced concrete structures increasing their lifetime if these remain in favorable hydrothermal conditions for a very long time. In saturated environment causing continuous cement hydration, concrete will have very high density and strength level, maintaining highly alkaline environment protecting steel reinforcement from corrosion.

The monograph [8] considers in detail corrosion resistance of concrete and reinforced concrete in various aggressive environments, it discusses the required mechanical properties and material compositions of concrete providing long-term resistance under these conditions. The study also overviews the extensive research, the findings of which have been implemented into production practice. The author substantiates the requirements for materials used in concrete production, for its quality indicators as regards the strength and durability. Compliance with these requirements would guarantee the long-term preservation of reinforced concrete structures in a good condition.

Tables 1 and 2 present estimated service life for concretes of various compositions depending on the concentration of sodium sulfate in the solution based on the implemented experiments [8]. Testing conditions provided for complete immersion of samples into a sodium sulfate solution. The service life was calculated according to the number of sulfate ions absorbed during a 3-year long testing of samples from the mortar part of concrete in a 1 cm-thick layer.

Table 1. The service life of concrete based on sulfate-resistant Portland cement in sodium sulfate solutions assuming various concentrations

Concentration of sulfate ions, mg/l	Service life of concrete, years		
	W/C= 0.4 W8—W10	W/C= 0.32 > W20	W/C= 0.29 > W20
5,000	130	380	430
12,000	50	115	110
50,000	13	29	40

Table 2. The service life of concrete based on Portland cement produced by the Voskresensk Plant

Concentration of sulfate ions, mg/l	Concrete service life, years		
	W/C= 0.4 W8—W10	W/C= 0.32 > W20	W/C= 0.29 > W20
5,000	100	145	370
12,000	25	40	35
50,000	7	6	8

The experiments showed that the service life depends on the type of cement, the concentration of sulfate ions (aggressive solution), the density of concrete, which is integrally characterized by the water-cement ratio and its water resistance.

It was noted that, other things being equal, concrete based on sulfate-resistant Portland cement was expected to have the longest service life. Concretes based on Portland cement with superplasticizer (C-3 was discussed in the book [8]) and microsilica (MK) added to it were found to have similar service lives.

Tables 1 and 2 demonstrate that the low water-cement ratio (W/C) is essential for the dense structure of the material produced, consequently, for its long service life. Correct choice of the concrete composition provides high water resistance due to the resulting small and very fine porosity.

The publication [8] also presents the service life estimated for a cement-sand mixture in a sodium sulfate solution with a concentration of 10,000 mg/l based on four types of cement provided as examples: Volsk sulfate-resistant cement, Portland cements produced by the Voskresensk, Topkinsk and Mikhailovsk cement plants.

The following types of solutions were tested: without additives, with an addition of superplasticizer C-3, microsilica and superplasticizer C-3, the water-cement ratio was taken equal to 0.38; 0.40 and 0.43 respectively. The tested compositions actually represented the mortar part of Class B-45-B55 concrete.

Positive results in terms of durability were obtained for the cement-sand mortars based on sulfate-resistant Portland cement with the addition of C-3 and with the addition of MK and C-3. Service lives ranging from 500 to 810 years were predicted for the first and the second option respectively.

When the service life of concrete of up to 500—810 years was discussed, no account was taken of the fact that the containers were constantly kept in stagnant water which was referred to as RW Class 2 disposal conditions provided waste packaging into reinforced concrete containers NZK-150-1.5P [2], [8]: the cement was supposed being constantly and continuously hydrated with its strength level growing slowly, the porosity level decreasing while the protective properties of reinforcement against corrosion would increase [2]. This process (infinitely long stay of the container in almost stagnant non-aggressive water due to the building envelope and the bentonite backfill) should also extend the service life of the containers in addition to the time periods mentioned above.

The paper [4], provides calculated service life of concrete according to the forecasts provided by the Japanese scientists. According to their results, the current maturity level in concrete production may provide a service life of up to 500 years. It was also noted that the material provided reliable protection of metal fittings against corrosion.

Another publication presented by a Japanese expert (Okad K. Durability of concrete constructions // Cement and Concrete, 1986, no. 470), cited in [2], notes that the service life of ordinary concrete in a non-aggressive environment is unlimited. Therefore, for the considered structure or product its quality indicators are believed to be adequate as regards relevant environmental and operating conditions.

Specifications for the basic NZK-150-1.5P container and its structural material

It's a reinforced concrete protective non-returnable container of the NZK type designed for solid and solidified radioactive waste, labelled as NZK-150-1.5P, manufactured according to specification L.65.555.00.00.000, designed to accommodate solid and solidified very low-level, low-level and intermediate-level removable radioactive waste, as well as for waste conditioning, transportation, long-term storage and disposal.

Experiments, as well as computational and analytical research allowed to evaluate and demonstrate the durability of this container amounting to at least 300 years.

Tables 3 and 4 present the main characteristics of this container and its structural material.

Table 3. Weight and size characteristics of NZK-150-1.5P container

Characteristics	Value
Height, mm	1,375
Width, mm	1,650
Length, mm	1,650
Minimum wall thickness (not accounting for the metal insert), mm	150
Minimum lid thickness (not accounting for the metal insert), mm	150
Minimum bottom thickness (not accounting for the metal insert), mm	150
Container capacity, m3	1.5
Weight of an empty container with lid (plug, insert), t, ± 4 %	4.5—4.7
Weight of NZK with RW accounting for primary packaging (not more than), t	7.6—8.5
Number of tiers when stacked, pcs.	6—8 depending on the package weight

Table 4. Characteristics of the structural material

Characteristics	Value
Compressive strength, MPa	68—75
Axial tensile strength, MPa	3.5—4.2
Bending tensile strength, MPa	7.0—8.0
Modulus of elasticity, MPa	4,100—4,500
Ultimate compression strain	$2.4 \cdot 10^{-3}$—$2.5 \cdot 10^{-3}$
Frost resistance of the studied concretes	More than F400
Water permeability of the studied concretes	More than W14
Diffusion coefficient for ^{137}Cs in concrete given water saturation of 5—8 %	Less than $1.0 \cdot 10^{-12}$ m^2/s

Requirements for RW Class 2 and 3 packages

The requirements established for the packages intended for RW Class 2 and 3 differ basically due to the RW activity levels (Table 5) and the time period during which the packages should be able to maintain their sealing capacity (Table 6).

Table 5. Characteristics of RW Class 2 and 3 (for disposal purposes)

Class	Waste category	Specific activity, Bq/g			
		Tritium	β-emit.	α-emit.	Transuranic elements
1	High-level (heat generating)	$>10^{11}$	$>10^{7}$	$>10^{6}$	$>10^{5}$
2	High-level (up to 100 W/m^3)	$>10^{11}$	$>10^{7}$	$>10^{6}$	$>10^{5}$
	Long-lived intermediate level	10^{8}–10^{11}	10^{4}–10^{7}	10^{3}–10^{6}	10^{2}–10^{5}
3	Intermediate-level	10^{8}–10^{11}	10^{4}–10^{7}	10^{3}–10^{6}	10^{2}–10^{5}
	Long-lived low-level	10^{7}–10^{8}	10^{3}–10^{4}	10^{2}–10^{3}	10^{1}–10^{2}

Table 6. Requirements for packages designed for various RW classes

Requirements	RW Class	
	2	3
Surface dose rate, mGy/h	not applicable	not more than 10 mGy/h
Mechanical compressive strength	not less than 10 MPa	not less than the one required for type A package, (not less than 5 MPa)
Rate of radionuclide release from the package (mass fraction of activity released from the RW package per year)	not applicable	not less than 10^{-2}/year for tritium; not less than 10^{-3}/year for β-, γ-waste; not less than 10^{-4}/year for α-waste
Sealing capacity of the package, years	not less than 1000	not less than 100
Heat generation by RW package	not less than 100 W/m^3	not applicable
Resistance to thermal cycles	maintaining strength and sealing capacity after 30 freeze/thaw cycles (−40…+ 40 °C)	maintaining strength and sealing capacity after 30 freeze/thaw cycles (−40…+ 40 °C)
Radiation resistance of RW packages	decrease in the strength level by not less than 20 % from the established limit given a dose rate of 10^{6} Gy or a forecasted exposure rate	decrease in the strength level by not less than 20 % from the established limit given a dose rate 10^{6} Gy or a forecasted exposure rate

RW Class 2 contains long-lived radionuclides, which is seen as a distinctive feature of this waste class responsible for the long time periods while it potentially remains hazardous. In addition, Class 2 waste is divided into two categories: high-level, with limited heat release up to 100 W/m^3, and long-lived intermediate-level waste.

These features are responsible for the key differences in the requirements established for Class 2 and 3 RW, namely, those associated with the mechanical strength and retention of its sealing capacity.

Requirements for Class 2 and 3 RW packages are characterized by another feature, which complicates the production of containers suitable for RW Class 2 packaging: the time period during which the package shall maintain its sealing capacity amounting to 1,000 years. It should be noted that this time period has been substantiated neither by any scientific research nor a feasibility study, but was ruled only by the insufficient knowledge on the protective properties of all barriers constituting to the multi-barrier RW disposal concept.

This excessive requirement hinders the development and the use of containers intended for RW Class 2 conditioning, on the one hand, since no methods are available to substantiate the package durability for 1,000 years and, on the other hand, due to the high costs involved.

Disposal conditions for Class 2 RW packages in a deep disposal facility

In accordance with the disposal strategy [17], Class 2 RW packages will be disposed of in underground excavations (chambers) at a depth of approximately 500 m in watertight gneiss formations. The rocks are characterized by high strength and low hydraulic conductivity as regards the groundwater (GW) flows.

The average mineralization level for GW is approximately 350 mg/l, pH = 7.5. Their average composition is shown in Table 7 [18].

Table 7. Composition of natural groundwater at the Yeniseyskiy site

Anion	Content		Cation	Content	
	mol/l	mg/l		mol/l	mg/l
Cl^-	$7{,}14 \cdot 10^{-4}$	25,0	Na^+	$1{,}40 \cdot 10^{-3}$	32,0
SO_4^{2-}	$1{,}62 \cdot 10^{-4}$	15,5	K^+	$1{,}15 \cdot 10^{-4}$	4,6
CO_3^-	$9{,}50 \cdot 10^{-5}$	5,7	Mg^{2+}	$4{,}94 \cdot 10^{-4}$	11,8
HCO_3^-	$3{,}2914 \cdot 10^{-3}$	200,0	Ca^{2+}	$1{,}21 \cdot 10^{-3}$	48,0

According to the above data, bicarbonates, sulfates and chlorides are viewed as the key anionic

GW components, whereas cations are mainly represented by calcium, sodium and magnesium.

The properties of water can be judged from the data in Table 8, which indicate that given the siting conditions of the Nizhnekanskiy rock mass with low permeability soils, the groundwater can be characterized as a non-aggressive medium for the concrete. Otherwise, these enclosing rocks could not be considered favorable for DGR siting purposes.

Table 8. Main features of non-aggressive water*

Indicator of aggressive nature	High- and medium-permeable soils, $K_f > 0.1$ m/day	Low-permeable soils, $K_f < 0.1$ m/day
Bicarbonate alkalinity HCO_3, mmol/l	More than 1.4	Not regulated
pH	More than 6.5	More than 5
Free carbonic acid CO_2 content, mmol/l	Less than 15	Less than 55
Content of magnesia salts (per Mg ion), mg/l	⩽1,000	⩽2,000
Content of caustic alkalis (for K and Na ions), g/l	⩽50 (in case of water-retaining structures ⩽30)	⩽80
Sulfate content (per SO_4 ion), mg/l	Less than 300	Less than 300
Content of chlorides, sulfates, nitrates and other salts and caustic alkalis in the presence of evaporating surfaces, mg/l	Less than 10	Less than 10

*If the levels indicated in this table are exceeded, water aggressiveness level shall be evaluated in accordance with the requirements set forth in SP 28.13330.2017 Protection of Building Structures from Corrosion. Updated version of SNiP 2.03.11-85

After a disposal chamber is filled with waste, the gaps between the containers shall be filled with bentonite or a purpose-designed grout to establish a waterproofing barrier.

Within a few years or decades after the chamber backfilling and sealing is completed, hydraulic pressure in the disposal area gets restored: its level may amount to 5 MPa.

Temperature in the disposal chambers intended for long-lived intermediate-level waste Class 2 is believed to remain constant, ranging from 30 to 50 °C, since no heat is released by such waste. The impact of Class 1 high-level waste, namely, of its thermal field, will be limited since the thermal impact produced by the waste on the protective bentonite barrier should be limited to a temperature of no more than 90 °C, and the HLW and ILW disposal zones will be spaced by at least 10 meters of bedrock.

Factors affecting the structural material of NZK-150-1 container and their analysis

Container durability depends on its ability to maintain performance until a time period set by regulatory requirements. In case of waste disposal, it experiences mechanical and environmental impacts, as well as those produced by waste and its degradation products. Container durability will depend on the resistance of the structural material (concrete) to the external influences.

Listed below are the main types of impacts produced under disposal conditions on a package with its designs based on a reinforced concrete container of the NZK type:

- carbonization;
- frost deterioration;
- concrete corrosion;
- concrete biocorrosion;
- corrosion of steel fittings;
- radiation exposure;
- impact produced by RWmaterials.

Considered below are various factors affecting the durability of concrete and their impacts.

Concrete carbonization

Described below is the essence of the process called concrete carbonization [6]. Carbon dioxide, carbonates and bicarbonates from DGR groundwater enter into a chemical reaction with the calcium hydroxide present in the concrete in a free state. A strong compound is formed — calcium carbonate with its layer gradually moving deeper and deeper into concrete. Carbonization depth depends on its moisture content and the surrounding environment, but mainly on its density and permeability. In dense concrete, carbonization of calcium oxide hydrate $Ca(OH)_2$ and formation of calcium carbonate $CaCO_3$ occur only in the surface layer.

The solubility of calcium carbonate, other things being equal, is approximately 100 times lower than the solubility of calcium oxide hydrate, therefore, carbonization of concrete greatly increases its resistance during the development of type I corrosion.

At the same time, protective layer carbonization may decrease the alkalinity of the concrete surrounding the reinforcement (pH level drops from 12.5—13.5 to 7—8) and if it is not dense enough, the reinforcing steel corrosion may evolve. Corrosion process along with its propagation may cause cracks in the protective layer of concrete and its degradation.

However, since the containers are constantly exposed to stagnant water, concrete carbonization is excluded: it gets hydrated constantly and continuously, its strength level grows slowly, its porosity level decreases, whereas the anticorrosive properties of the reinforcement tend to increase [2], [8].

Moreover, in underwater structures constantly remaining under water, steel reinforcement corrosion does not occur since no oxygen is available [1], [2], [8].

It should be also taken into account that the gaps between the containers are supposed to be filled with cement mortar acting as a protective barrier against groundwater inflow. Moreover, it gets carbonized in the first place, thereby preventing the spread of hazardous components into container walls.

Therefore, concrete wall carbonization under DGR conditions is not considered as a dangerous factor that may decrease the container strength.

Frost driven degradation

Frost resistance of concrete is seen as a basic indicator characterizing its durability, which, in turn, depends on certain properties: the strength of the cement stone, ductility. However, the key one is the saturation degree and the pore space structure of the cement stone.

The process of RW Class 2 package disposal in DGR always provides for above zero temperature, which excludes the frost driven degradation factor.

Concrete corrosion

There are three types of concrete corrosion.

First type of concrete corrosion

The first type of corrosion comprises all those corrosion processes occurring in concrete when exposed to water with low hardness, when the cement stone components are dissolved and carried away by the water flows.

In case of concrete corrosion type 1, to predict the concrete durability and quantify the corrosion intensity, the following parameters can be calculated: lime leaching rate, the threshold water conductivity or the time period while the concrete strength level remains constant assuming water flowing through it or when the water washes over the concrete surface.

Considered below is the simplest method that can be used to calculate the service life of concrete and reinforced concrete structures when exposed to water under pressure that can be used to evaluate the risk of this corrosion type occurrence.

Table 9 presents the flowchart developed to calculate the service life of container given the impact of type 1 corrosion.

The case study considers a waste container disposed of in subsoil with a groundwater flow characterized by the following parameters: hydraulic slope — 0.013 m/m, hydraulic conductivity of the external environment — 730 m/year (sandy loam), filtration rate — 9.49 m/year. These indicators are considered typical for the soils at the site of the FSUE RosRAO's Leningrad branch of North-Western Territorial District and are considerably inferior to the conditions assumed under the conditions provided for RW Class 2 disposal in DGR.

Lime leachability was calculated for concrete assuming the W8 water resistance level (conservative approach), hydraulic conductivity factor ranging from $1{\cdot}10^{-10}$ to $6{\cdot}10^{-10}$ cm/s. It was demonstrated that its service life may range from 1,300 to 8,000 years with no expected decrease in its basic technical properties.

This indicates that at low filtration rates, being considered typical for RW disposal conditions, no water flows are basically present in concrete, and according to the calculations, the lime leaching process has practically no effect on its service life.

Table 9. Flowchart used to calculate the service life of concrete containers exposed to type 1 corrosion

Calculation algorithm	Model or Calculation Formula	Limits or Parameter Values
1. The amount of water seeping through the NZK wall	$V = K_ф \cdot \Delta H / X$ $K_ф$ is the hydraulic permeability factor; ΔH is the hydraulic slope; X stands for the wall thickness	ΔH is taken equal to 0.013 m/m; $X = 0.15$ m
2. The amount of lime that may leach out	$Q = K \cdot Ce \cdot \acute{\alpha}$ K is the percentage of CaO leaching; Ce is the content of cement in concrete; $\acute{\alpha}$ is CaO content in cement	K is taken equal to 10 %; Ce is taken equal to 0.4 g/cm^3; $\acute{\alpha}$ for Portland cement can be taken as 0.65.
3. Durability of concrete in the NZK walls	$T = q / V \cdot C$ C stands for the average concentration of lime in water	C is taken equal to 1.2 g/l

Concrete corrosion of type 2

The second type of corrosion considers cement stone degradation due to the impact of salt containing water that can enter into exchange reactions with the cement stone components. This process results in products that are either easily soluble or get segregated in the form of an amorphous mass having no binding properties. Due to these transformations, the cement stone porosity grows and, therefore, its strength level drops.

From a physical and chemical point of view, type 2 corrosion involves the following processes:

- penetration of an aggressive substance from the solution into the porous structure of concrete;
- chemical interaction of an aggressive substance with cement stone components resulting in soluble (or amorphous) products;
- release of soluble reaction products from concrete.

Corrosion driven by carbon dioxide waters is seen as a common form of concrete corrosion caused by natural water impact. H_2CO_3 acid is usually present in all waters. Biochemical processes occurring in water and in soil drive such enrichment. It should be also noted that the more is the amount of aggressive H_2CO_3, the higher are the acidic properties of the solution and its corrosion rate.

The rate of the second type corrosion depends on the rate of carbon dioxide inflow with groundwater. If no groundwater flow is present or it's negligible, this type of corrosion may not produce any impact on the concrete durability.

Concrete corrosion type 3

The third type of corrosion involves the processes triggered by sulfate impact. Cement stone pores accumulate poorly soluble substances contained in water or the products of their interaction with its constituents. Their accumulation and crystallization in the pores may cause significant tensile stresses in the pore walls leading to cement stone degradation. Interaction of gypsum dissolved in water with tricalcium hydroaluminate according to equation (3) is considered a characteristic type of such sulfate corrosion:

$$3CaO \cdot A1_2O_3 \cdot 6H_2O + 3CaSO_4 + 25H_2O = \\ = 3CaO \cdot A1_2O_3 \cdot 3CaSO_4 \cdot 31H_2O \qquad (3)$$

In this case, sparingly soluble calcium hydrosulfoaluminate is generated: when it gets crystallized, it absorbs large water amounts causing its expansion and its volume grows by approximately 2.5 times, which has a strong destructive effect on the cement stone.

Corrosion impacts produced by various waters can be avoided or mitigated through the implementation of certain engineering measures, improved concrete production process, as well as the use of cements with certain mineralogical composition and a required content of active mineral additives.

Based on the comparison between the ionic composition of groundwater (Table 7) and water parameters (Table 8), one can state that the environment cannot be considered aggressive for the concrete and, moreover, this type of corrosion has practically no effect on container durability.

Corrosion of steel reinforcement

Corrosion of steel reinforcement is seen as another factor potentially causing degradation of reinforced concrete structures [2]. Their long-term reliable performance is primarily provided by reinforcement protection against corrosion under appropriate operational conditions. Its accommodation inside high-quality concrete is seen as an effective method in this case, i.e., the reinforced concrete structure itself provides the long-term preservation of steel reinforcement in concrete.

In underwater structures constantly remaining under water, steel reinforcement corrosion is absent due to the lack of oxygen [1], [2], [8]. As noted above, Class 2 RW packages will be disposed of at a depth of about 500 m. After that, the gaps between the packages and the walls of the excavation will be backfilled with bentonite mixture or special cement mortar. After some time, the entire disposal area will be saturated with groundwater, and due to extremely low GW flow rate, oxygen transfer will be limited, which, in combination with the carbonization process, prevents the corrosion of steel reinforcement.

Biocorrosion of concrete

Concrete biocorrosion caused by the action of an aggressive environment and microorganisms is seen as a most important factor driving concrete degradation.

There are two main types of biocorrosion: bacterial and fungal. Among various bacteria, nitrifiers, thionic, iron and silicate bacteria, etc. are involved in cement concrete corrosion. Mycelial fungi, namely, *Penicillium, Aspergillus, Trichoderma, Cephalosporium* are responsible for fungal corrosion [19].

Biodegradation effects are mainly limited to disturbed adhesion of concrete components due to their exposure to mineral or organic acids and enzymes, as well as due to chemical reactions taking place between the cement stone of mortars and concretes and microbial products [20].

The durability of cement concretes under biological imoacts largely depends on the material porosity: increased porosity increases the permeability for microorganisms, which contributes to a decreased strength of composites [19].

Concrete resistance may be increased by the introduction of a finely dispersed filler, microsilica, into cement compositions. This additive has positive effect on the structure formation and the porosity level of the cement stone. Microsilica mainly consists of amorphous silica, which, interacting with calcium hydroxide, contributes to the formation of an additional amount of low-basic calcium hydrosilicates promoting cement stone compaction [19].

The biostability of cement materials can be effectively enhanced by reducing the content of dust and clay particles in crushed stone and fine aggregate — to no more than 1.0% (by weight), and the introduction of fungicidal additives into the concrete.

Taking into account the microbiological effect on concrete, container service life can be reliably predicted only based on large-scale model experiments in the biological URF zone, including sampling efforts and identification of local microflora, laboratory experiments and natural in situ experiments [21] .

Radiation exposure

Radiation resistance is characterized by the ability of a material to retain its structure and properties under radiation exposure during its service life. Cement materials are used widely in the construction of spent fuel pools and storage facilities for spent nuclear fuel with high-level neutron and gamma radiation [22].

It is noted in [23] that at a total dose of up to 190 MGy, radiation exposure produces no significant effect on the properties of ordinary concrete with a density of 2,200—2,400 kg/m^3, such as changes in its mass, compressive strength, elastic modulus, carbonization depth, pore distribution.

Radiolysis of free and bound water that may cause the formation of free hydrogen will not change the properties of concrete, since hydrogen tends to diffuse through the concrete wall due to sufficient gas permeability.

Exposure to radioactive waste materials

According to the requirements for the radioactive content [24], the waste should not contain any substances prone to explosion, that may react with water causing the release of self-igniting or flammable gases or form toxic gases, aerosols or fumes with air or other substances, infectious substances. The content of flammable and spontaneously flammable and complexing substances should be limited to no more than 1% by the weight of the radioactive contents available in the package. Free liquid should be less than 3% by weight of the material in the package.

Class 2 intermediate-level waste may include: graphite, metal, cement compound. This waste type fully complies with the listed requirements with a few more listed below that shall be added.

The waste should not contain substances that may cause concrete corrosion of the second and third types upon their interaction with water.

When the free space in the container is filled, the material should not contain these substances as well, it should not interact with the concrete walls of the container, put pressure on the walls of the container when the cement mortar or the swelling material is poured.

If necessary, a metal insert can be installed inside the concrete containers and/or an anti-corrosion coating can be applied to the inner container surface.

Requirements to concrete containers for RW Class 2

The requirements presented below were proposed based on the studies performed and the experience of concrete and reinforced concrete structure operation. Compliance with these requirements may provide a service life of several centuries assuming the NKM DGR conditions.

Mechanical quality indicators:

- compressive strength — class B50 and higher;
- axial tensile strength — class Bt2.4 and higher;
- modulus of concrete elasticity, Ex — 38,000 MPa and higher.

The rest of the indicators were set forth according to SP 63.13330.2018 for concrete B50.

Physical quality indicators:

- water resistance — W20 and higher;
- average density — D2400—D2550 kg/m^3;
- frost resistance — F300 and higher.

Material requirements:

Portland cement class CEM I 52.5, GOST 311082016. Sulphate-resistant cement CEM I 42.5 SS, GOST 22266-2013.

Additives to concrete:

- superplasticizing and water reducing (mandatory);
- providing the preservation capacity and mobility (recommended);
- reducing hydraulic conductivity (recommended);
- increasing corrosion resistance — silica fume, grades MK-85 or MKU 85 (recommended).

Coarse aggregate according to GOST 8267-93, ed. 2018:

Crushed stone from dense rocks with an average density of 2.65 to 3.0 g/cm^3 with fractions from 5 to 10 mm and from 10 to 20 mm or a mixture of fractions from 5 to 20 mm. Grade according to the crushed stone — “1200”. The content of dust and clay particles by weight is not more than 1.0 %, the clay content in lumps is not more than 0.25 % by weight. Harmful components and impurities should be absent.

Fine aggregate according to GOST 8736-2014, ed. 2019:

Class I sand, sand group: coarse, medium. As it comes to other quality indicators, the sand shall comply with the requirements established for class I sand and the above group.

Discussion of the results

The above brief overview of research on the concrete durability allows to conclude that modern methods of its production enable its application in the construction of critical buildings and structures with an assigned service life of up to 500 years.

The studied hydrogeological conditions at the NKM DGR site have revealed their non-aggressiveness with respect to concrete. Most important factors affecting its durability, as well as the ability to maintain a high pH level in the DGR near field for many thousands of years were studied with no reasons identified that could trigger some important decrease in the key quality indicators of the container structural material assuming RW package dusposal in DGR. However, to date no research has been performed that could demonstrate the integrated effect produced on concrete (yet no such assessment has been done to study other materials) under the disposal conditions, which include joint chemical, microbiological, thermal and radiation effects. These studies should be performed in the URF under conditions being considered similar to the disposal ones.

To produce containers that would to the fullest extent possible comply with the regulatory requirements for RW Class 2 packaging, particular composition and production method were developed to provide such characteristics of the concrete that would ensure the preservation of protective properties within a time period of a few centuries. Actual durability of such containers cannot be literally estimated since no methods are available to provide relevant forecasts covering such a long timeframe.

In this regard, it's believed necessary to develop a method that would demonstrate the reliability of structural container materials for RW Class 1 and 2. It seems also advisable to introduce necessary amendments to the regulatory framework (NP-093-14) establishing the timeframe for the preservation of its protective properties based on the long-term safety assessment of the disposal system.

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