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ASSESSMENT OF THE RELIABILITY OF A CONCRETE CASK SHELL OF THE DRY STORAGE OF THE SPENT NUCLEAR FUEL

В.І. Ковальчук, І.Л. Козлов, О.А. Дорож, К.О. Сова. **Оцінка надійності бетонної оболонки контейнеру сухого сховища відпрацьованого ядерного палива.** Експлуатація АЕС супроводжується накопиченням відпрацьованого ядерного палива, яке класифікується як високоактивні ядерні відходи. Застосування сучасних технологій сухого довготривалого зберігання палива в умовах АЕС вимагає оцінки надійності обладнання, зокрема, обичайок гермокошиків з точки зору їх деградації з часом. Мета дослідження – розглянути можливість ймовірнісної оцінки надійності бетонної оболонки контейнеру сухого сховища відпрацьованого ядерного палива. Зберігання ядерного палива, що відпрацювало, передбачає створення сховищ довготривалого зберігання. Сховище з ядерним паливом розглядається як ядерна установка і потребує, відповідно до Закону України «Про використання ядерної енергії і радіаційної безпеки», оцінки його надійності на весь термін експлуатації, тривалість якого має бути не менш 50 років. Виконання такої оцінки можливо на основі побудови структурної схеми елементів технологічної схеми і їх ймовірнісних розрахунків. Дослідження побудовано на аналізі конструктивних особливостей елементів обладнання, ймовірнісних розрахунках надійності конструкції в цілому і порівнянні їх з станом обладнання, що відпрацювало певний термін. Виконана розрахункова оцінка терміну служби вентильованого контейнеру, з урахуванням умов його експлуатації, довела, що він не перевищує 33 років. Візуальна та розрахункова оцінка стану поверхні бетону оболонки контейнеру для різної тривалості зберігання показала, що при терміні зберігання 7…9 років спостерігається значне тріщиноутворення, що перевищує аналогічний показник природних порід в 3…5 разів. Доведена залежність оцінки надійності захисної оболонки від повноти побудови функціональної структурної схеми, можливість розрахункової оцінки терміну надійної експлуатації оболонок контейнерів, виявлена деградація поверхні оболонок контейнерів за термін менший за розрахунковий. Обчислено орієнтовне значення надійності бетонної оболонки вентильованого контейнеру зберігання. Оцінено порушення поверхневої монолітності бетонної оболонки в залежності від тривалості зберігання контейнеру відпрацьованого ядерного палива. Доведено доцільність систематичних оглядів та відновлювальних робіт з поверхнями оболонок.

Ключові слова: контейнер, надійність, бетонна оболонка, зберігання, ядерне паливо

V. Kovalchuk, I. Kozlov, O. Dorozh,. K. Sova. **Assessment of the reliability of a concrete cask shell of the dry storage of the spent nuclear fuel.** Exploitation of NPP is accompanied by the accumulation of spent nuclear fuel, which is classified as highly active nuclear wastes. Application of modern technologies of dry long term storage of fuel in the conditions of NPP requires the estimations of reliability of equipment, in particular, sealed basket shell from the point of view of their degradation in course of time. Research aim is to consider possibility of probabilistic estimation of reliability of concrete shell of the cask for dry storage of spent nuclear fuel. Storage of spent nuclear fuel envisages creation of depositories of long term storage. Nuclear fuel storage is examined as nuclear installation and on the Law of Ukraine “About use of nuclear energy and radiation safety” needs estimation of his reliability on all term of exploitation, duration of that must be no less 50 years. Implementation of such estimation maybe based on construction of flow diagram of elements of flowsheet and them probabilistic calculations. Research is built on the analysis of structural features of elements of equipment, probabilistic calculations of reliability of construction on the whole and comparing of them to the state of equipment that worked a certain term. A calculated lifetime of the ventilated cask has been fulfilled, taking into account the conditions of its operation, has proved that it does not exceed 33 years. The visual and approximate assessment of the surface of the concrete of the cask shell for different storage term showed that during the storage period of 7...9 years, there is a significant cracking that exceeds a similar figure of natural breeds in 3...5 times. The dependence of the reliability of the shell on the completeness of the construction of the functional structural scheme, as well as on the possibility of a calculated

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estimation of the period of reliable operation of the cask shell is proved. We observed degradation of the surface of the casks shells for a period less than the estimated. The reference value of reliability of concrete shell of the ventilated cask is calculated. Violation of superficial monolithic nature of concrete shell is appraised depending on shelf-life to the spent nuclear fuel cask. Expediency of systematic reviews and modernisation is well-proven with the surfaces of shells.

Keywords: cask, reliability, concrete shell, storage, nuclear fuel

Introduction. Exploitation of the NPP is accompanied by the accumulation of spent nuclear fuel (SNF), which is subject to further processing in order to obtain fuel-forming components and the release of solid radioactive waste (Fig.1) [1].

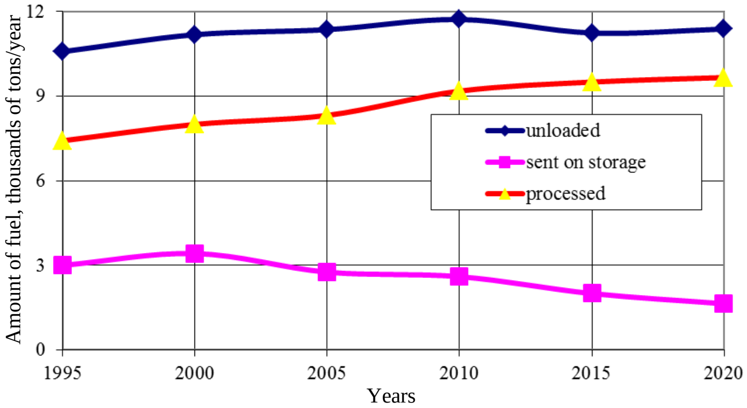


Fig. 1. Accumulation of spent fuel in the world for a year

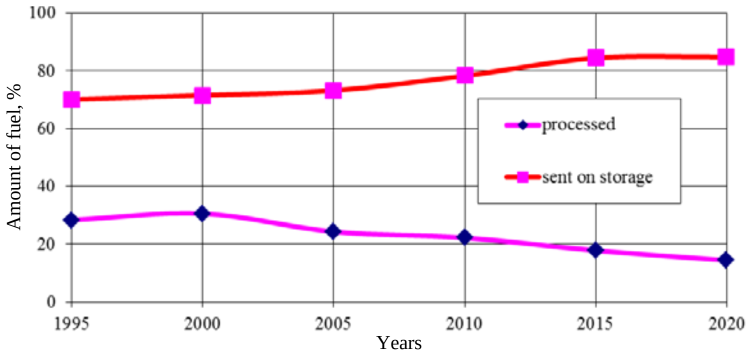


Fig. 2. Ratio of shipped and recycled spent fuel in the world

The design decisions of the NPP provide for the export of spent fuel that was spent after the endurance in the pools. On a global scale, nuclear fuel storage of nuclear power plants that has worked out involves the creation of permanent storage facilities of long-term storage.

The spent nuclear fuel is classified as high-level nuclear waste, and its storage is considered as a nuclear installation.

In accordance with the Law of Ukraine “About Nuclear Energy Use and Radiation Safety”, the decommissioning of the storage facility is preceded by a survey and a comprehensive analysis of storage facilities, in particular, the state of the outer surface of the sealed basket shells in terms of surface defects and the condition of the outer surface of the concrete of ventilated casks in terms of cracks, damages and other defects. This makes it necessary to assess the reliability of storage facilities.

Analysis of recent research and publications. Storage of spent nuclear fuel at NPPs in the world. When storing spent fuel assemblies (SFA) in the pool of exposure for 3…5 years, the residual heat and radioactivity of fuel are significantly reduced. Such fuel can be safely processed or stored dry in special containers that provide effective heat removal from the SFA and sufficient biological protection against radiation exposure to NPP personnel and the natural environment.

There are three directions of treatment of spent fuel:

– complete or partial processing of spent fuel in order to use fission products for the manufacture of MOX fuel;

– development and implementation of projects for the final disposal of spent nuclear fuel;

– postponing the final decision on the issue of spent fuel management (“wait and see” position).

The amount of fuel sent for burial or long-term storage is more than 70 % of all unloaded fuel, and by 2020 it will reach 85 % (Fig. 2).

The total annual amount of reprocessed spent fuel is concentrated in four countries (Table 1) [1].

Table 1

Volumes of reprocessing of spent nuclear fuel in power light water reactors in the world

Country	France, La Hague	UK, Selfield	Russia, Chelyabinsk (VY “Mayak”)	Japan
Processing volume of spent fuel, t/year	1600	850	400	90

Most countries have postponed the final decision on the problem of spent fuel management, keeping it in special wet or dry storage.

The two most common types of SNF dry storage technologies are the most common:

– cask storage;

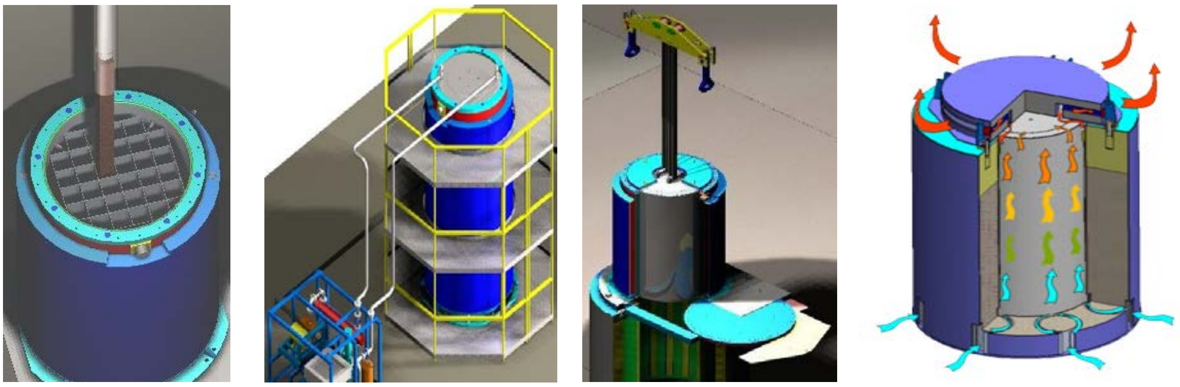
– modular storage.

In 1986, at the Sarry NPP site in Virginia, when the US nuclear regulator issued a license for the operation of a dry storage facility for SNF, the technology for the storage of spent nuclear fuel was started.

Casks can be concrete or metal. The heat removal is carried out at the expense of natural convection of the ambient air.

Operation on the preparation and filling of SNF casks is carried out at the NPP site, after which a fuel container is sent to the storage site. There are four main stages (operations) of the technology of dry container storage of spent nuclear fuel (Fig. 3).

The purpose of the study. The need to assess the reliability of the storage system of spent nuclear fuel. The absence of facilities for the reprocessing of spent fuel in Ukraine led to the decision to prolong the storage of spent fuel in nuclear power plants.



a *b* *c* *d*

Fig.3. Stages (operations) of technology for dry storage of nuclear fuel: the case of SNF cask storage is located in a sealed metal basket (a); the cask is filled with inert gas (usually helium) (b); the basket is located in the case of a protective container (c); the sturdy construction of the cask body serves as a radiation protection, and also prevents damage to the metal basket (d)

At the Zaporizhzhya NPP the technology of dry ventilated cask storage VSC-24 of the American company Duke Engineering and Services has been well-proven for 15 years. It is designed for operation for 50 years, but there are no reliable equipment estimations for its realization. The purpose of the work is to evaluate the components and the system as a whole.

System of ventilated storage cask and assessment of its reliability. The main elements of the VSC-WWER cask system (ventilated storage cask) are the multi-assembly sealed basket (MSB) (Fig. 4, *a*) and a ventilated concrete cask (VCC) (Fig. 4, *b*) [2, 3].

The casual MSB is a welded structure consisting of a bottom, a cylindrical part and a block of hexagon tubes (Fig. 4, *a*). The latter is designed for the placement of 24 spent fuel assemblies (SFA) and assembled from hexagon tubes specially made

The outer surface of the case is covered with epoxy enamel to protect against corrosion, aggressive media and facilitate decontamination. The inner surface of the body of the MSB and the internalbody devices is the first coat. The basket is designed for load when falling on the side surface and bottom with an acceleration of 40 g, without deformation, in which fuel assemblies could be damaged. The protective cover of the basket is made of two steel sheets, among which is the layer of neutron protection from material YH-277. For feeding/pumping water or gas-air mixtures in the protective cover, there is a threaded and quick coupling. The power cover is installed over protective, provides transportation of the MSB for operations.

a *b*

Fig. 4. Design of a container for dry storage of spent nuclear fuel: a multi-seal sealed basket (a), reinforced concrete cask (b)

Ventilated concrete cask (VCC) provides structural resistance, protection against radiation and cooling the basket for storage by natural convection (Fig. 5, *b*). The thick concrete walls of the cask limit the radiation dose rate to 10 mbar/h at a distance of 1 m from the outer surface. Air inlet and outlet channels are covered with steel. The inner cavity forms a lining from the steel cylinder. The outer reinforcement frame is formed by vertical cores with hook and horizontal rod with a bracket (ring). The main structural parameters of VCC are given in Table 2.

Table 2

Basic design parameters of a ventilated concrete cask

Parameter	Component		
	concrete shell	facing	cover
Outer diameter, m	3.378	2.007	2.1844
Inner diameter, m	2.007	1.854	–
Thickness, m	0.686	0.076	0.057
Height, m	5.809	5.200	–
Material	concrete from portland cement	carbon steel A36	–

The lid of the concrete cask provides additional protection of the baskets from the influence of the environment and the impact of flying objects raised in the air tornado. The lid is screwed with bolts and is equipped with special position indicators on two of them, to detect attempts to unauthorized removal of the lid. The bottom of the concrete cask is a steel sheet of 9 mm thick, which covers the bottom and completely provides the content of concrete inside with an accident with a fall and impact on the bottom.

The VSC project includes criteria related to weather conditions of the environment and natural phenomena, mechanical loading, and nuclear safety [4]. The base temperature for thermal calculations of cycles is 24 °C. Fluctuations of temperatures are limited by the interval –40 °C in the absence of solar loads and +42 °C in the presence of solar loads. The wind load is taken to be 781 kg/m^2. The cask is capable of withstanding the impact of immersion at a depth of 51.2 m and a flow of water at a speed up to 7.62 m/s. Allowable snow and ice load is not less than 489 kg/m^2. Seismic stability in each of the mutually perpendicular horizontal directions of soil acceleration is not less than 0.2 g, and the vertical acceleration of the soil, which occurs simultaneously, is up to 0.14 g. From the point of view of the mechanical load, there are taken into account the weight, loading pressure during operations with SFA, thermal stresses, obstacles when carrying the storage basket from the reloading container to a concrete container, violation of normal conditions during transport and technological operations (personnel errors)

Nuclear safety is ensured by the guaranteed preservation of sub criticality not less than 5 % when pouring non-circulated water. The listed criteria allow to assume the effective operation of the VSC-VVER system under different conditions.

Results. In assessing the reliability of the VSC-VVER, as in any system, it is necessary to determine the probability of its normal functioning, taking into account three types of failures: unexpected (catastrophic), gradual (parametric), bounding [5]. Each type of refusal is an independent event. The probability of a good work of the product

$$P(t) = P_a(t)\,P_b(t)\,P_c(t),$$

where $P_a(t)$ – the probability of fail-safe work under catastrophic failures;

$P_b(t)$ – probability of failure-free operation at parametric failures;

$P_c(t)$ – the probability of failure-free operation with intermittent deviations (poorly subordinate to accounting when calculations are taken $P_c(t)=1$).

To calculate the reliability of the faultless operation of the shell is a functional structural scheme, which includes all the elements necessary for the implementation of the main function and the schedule of its work for the entire service life.

Failure of such a system and its individual elements is understood as a disruption of disability in the event of destruction.

The norm of reliability is established in the form of the probability of faultless work $P(t)$, or the average time of fail-safe work T_m. When estimating the assumptions were made:

– probability of failure-free operation in parametric and secondary attempts $P_b(t)=1$ і $P_c(t)=1$;

– the law of changing probabilities under catastrophic deviations – exponential;

– all items of the product are equally reliable.

Functional structural scheme. The cask consists of two components or blocks:

1. Multi-purpose sealed basket (MSB): welded lining in the complete set (bottom, cylindrical part, block of hexagon tubes), protective cover of basket of two steel sheets and a layer of neutron protection, threaded connection for drainage pipe, quick coupler for filing (pumping). The protective cover is welded to the basket case. Power cover in the form of a steel disk with transparent holes for access welded to the body;

2. Ventilated concrete cask (VCC): inside is lined with a steel cylinder, an external welded reinforcing frame with vertical rods and horizontal rings and concrete fillings. The bottom of the cask is made of steel sheet. The lid of the cask is screwed with bolts.

The fixed lifetime of the VSC-VVER WE is 50 years or hours.

Requires probability of failure-free operation at the level of P=0.96.

The probability of failure-free operation of each component is determined by known schemes (Table 3).

From the above calculation, it should be noted that based on assumptions, the reliability of the system, taking into account the conditions of its operation, is almost 10 times less than the declared one, and the concrete mantle, without allocation in a separate group of overlaid elements of the frame, can serve about 60 % of the claimed term.

Table 3

The probability of failure of each component

№	Indicator		Unit of measurement	Calculated formula, numerical value
1	Number of calculated elements of reliability of block 1		Units	7
2	Number of calculated elements of reliability of block 2		Units	4
3	Total number of calculated reliability elements		Units	$N = \sum_{1}^{2} n_i = 7 + 4 = 11$
4	The average value of the bounce rate, which is acceptable for the system as a whole		1/hour	$P = e^{-\lambda t_0}$, where $\lambda = -\frac{\ln P}{t_0} = -\frac{\ln 0.96}{400000} = -\frac{-0.04082}{400000} \approx -1.02 \cdot 10^{-7}$
5	The average value of the bounce rate, which is acceptable for the elements		1/hour	$\lambda_i < \frac{\lambda}{N} = \frac{1.02 \cdot 10^{-7}}{11} = 9.28 \cdot 10^{-9}$
6	Probability of fail-safe work for	separate blocks	–	$P_i = e^{-\lambda_i n_i t_0}$ or
		block 1	–	$P_{\mathrm{I}} = e^{-9.28 \cdot 10^{-9} \cdot 7 \cdot 400000} = -e^{-0.026} = 0.974$
		block 2	–	$P_{\mathrm{II}} = e^{-9.28 \cdot 10^{-9} \cdot 4 \cdot 400000} = e^{-0.0148} = 0.985$
		system as a whole	–	$P = P_{\mathrm{I}} \times P_{\mathrm{II}} = 0.985 \times 0.974 = 0.96$
7	Correction factor K_λ for operating conditions in stationary terrestrial devices		–	$K_\lambda = 10$
8	The probability of failure-free operation for individual units, taking into account the working conditions	separate blocks	–	$P_i = e^{-\lambda_i n_i t_0 \cdot K_\lambda}$
		block 1	–	$P_{\mathrm{I}} = e^{-9.28 \cdot 10^{-9} \cdot 7 \cdot 400000 \cdot 10} = e^{-0.26} = 0.771$
		block 2	–	$P_{\mathrm{II}} = e^{-9.28 \cdot 10^{-9} \cdot 4 \cdot 400000 \cdot 10} = e^{-0.148} = 0.898$
		system as a whole	–	$P = P_{\mathrm{I}} \times P_{\mathrm{II}} = 0.771 \times 0.898 = 0.692$
9	The lifetime of the HVAC-WWER, taking into account the working conditions		hour/years	$t_0 = -\frac{\ln P}{\lambda} = -\frac{\ln 0.692}{400000} = -\frac{-0.04082}{-1.02 \cdot 10^{-7}} \approx 40019.6$ hour or 4.57 years
10	Service life of the CFC, taking into account working conditions		hour/years	$t = \frac{\ln P}{-\lambda n K_\lambda} = -\frac{\ln 0.898}{9.28 \cdot 10^{-9} \cdot 4 \cdot 10}$ $t = \frac{-0.1076}{-9.28 \cdot 10^{-9} \cdot 4 \cdot 10} = 289870.7$ hour or 33.09 years

Zaporizhzhya NPP received a license for the introduction into the experimental and production operation of the first three containers of the dry spent fuel storage facility (DSFSF) in 2000 year. In the same year, the second power unit of the station started loading SFA into the first multi sealed basket of a ventilated cask.

Storage area, designed for 380 casks; according to the given schedule, the arrival of casks is capable of receiving all the fuel of the station until it is exhausted from its exploitation resource (Figs. 5 and 6) [6].

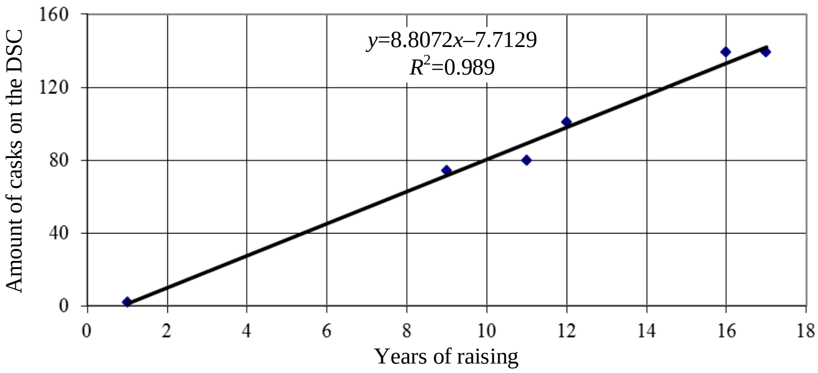


Fig. 5. Number of containers at the ZNPP DSFSF site

Fig. 6. The dry spent nuclear fuel storage site

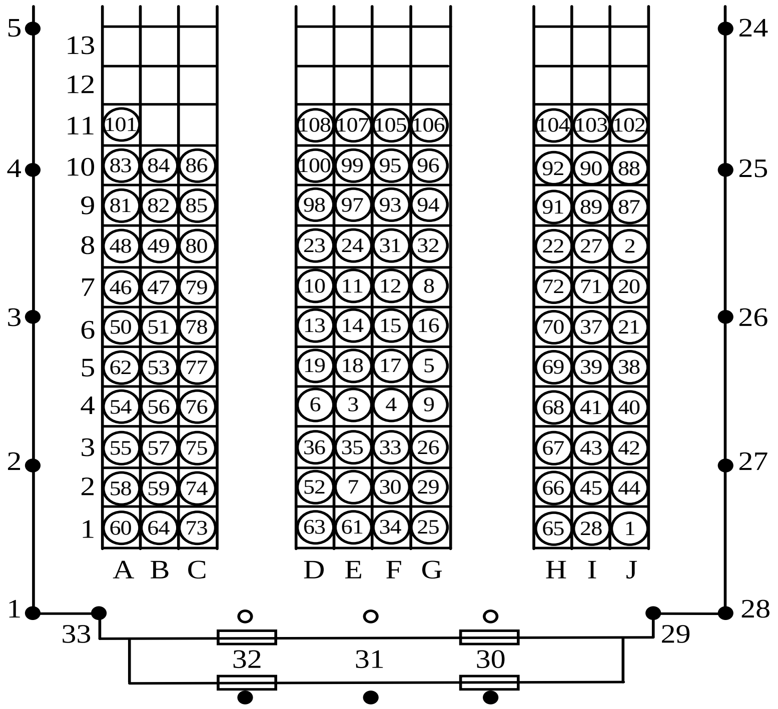
The condition of the outer shell of the cask when placed on a long storage indicates its monolithic and homogeneity (Fig. 7).

Increased sample (Fig. 10) from the illustration in Fig. 6, made in 2016 and in accordance with the cartograms (Fig. 8), stood at the site of 7 and 9 years, indicating a violation of the homogeneity of the surface, manifested in the form of significant formation of cracks.

Fig. 7. VSC-WWER at the moment of installation in storage

a *b*

Fig. 9. The state of the cask surface after being in place of storage:
a – 9 years (No. 60, 2007);
b – 7 years (No. 73, 2009)



	A	B	C	D	E	F	G	H	I	J
13										
12										
11	101			108	107	105	106	104	103	102
10	83	84	86	100	99	95	96	92	90	88
9	81	82	85	98	97	93	94	91	89	87
8	48	49	80	23	24	31	32	22	27	2
7	46	47	79	10	11	12	8	72	71	20
6	50	51	78	13	14	15	16	70	37	21
5	62	53	77	19	18	17	5	69	39	38
4	54	56	76	6	3	4	9	68	41	40
3	55	57	75	36	35	33	26	67	43	42
2	58	59	74	52	7	30	29	66	45	44
1	60	64	73	63	61	34	25	65	28	1

Fig. 8. Mapping of VSC-WWER placement on storage site

For the quantitative estimation of fracturing, the parameter “total crack density” K_y, is the total length of the micro cracks ($\sum l_m$, m), is attributed to the surveyed area (S, m^2) [7]:

$$K_v = \frac{\sum l_m}{S}.$$

The magnitude of the specific density of cracks in the rocks used for the production of lining materials is (m/m^2): granites – 0.05...0.1; gabbro – 0.1...0.5; white marbles – 0.2...0.5; coloured marbles – 1.24...2.2 and more. Its values are given in the Table 4 for the surface of the concrete shell, in 3...5 times greater than the values characteristic of natural rocks.

Table 4

Characterization of fracture of the concrete shell at different operating times

Parameter		Unit of measurement	9 years			7 years		
			top	middle	bottom	top	middle	bottom
The length of the cracks	total	m	16.67	49.61	20.37	33.97	54.37	22.38
	relative	m/m^2	7.21	10.42	9.92	5.78	7.11	4.88
Intensity of occurrence	total	m/hour	1.85	5.51	2.26	4.85	7.77	3.20
	relative	m/(m^2 hour)	0.80	1.16	1.10	0.83	1.02	0.70
The difference in relative intensity between 9 and 7 years		m/(m^2 hour)	0.71	1.65	2.52	–	–	–

The analysis of fracture characteristics showed that in the largest degree of formation of cracks exposed to the middle part of the shell (more than 10 m/m^2) when stored for 9 years. There are also marks of corrosion of the frame reinforcement, indicating the penetration and accumulation of moisture in the cracks. In the future, this may cause destruction of the protective layer of the shell and the appearance of the frame reinforcement.

In the smallest degree, this is the upper part, which is about 1/3 of the height.

During the time, the cracking intensity is shifted to the bottom, and reaches a value of 1.10m/(m^2·year). Traces of accumulation of moisture appear along the cracks, indicating the penetration of moisture into the shell's depth. Estimating the crack opening of 0.3 mm, it is possible to assume the formation of channels for the transport of aggressive gases to the frame reinforcement and the further destruction of the welds of the frame. Proceeding from the performed analysis, it is possible to confirm the need for preventive inspection and restoration of the surface of the shell or the replacement of the concrete shell on the steel [7].

Conclusion:

1. Taking into account the conditions of VCC operation, which was about 33 years, approximate assessment of its lifetime was made;
2. A visual and approximate assessment of the surface of the concrete of the cask shell for different storage duration was performed; it has been shown that during the storage period of 7...9 years a significant cracking is observed that exceeds the similar indicator of natural breeds in 3…5 times;
3. It is expedient to recommend systematic reviews and restoration works with the surface of the shell.

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