ESTIMATION OF RADIOACTIVE WASTE ACTIVITY RESOURCES IN THE MOTHBALLED AND DECOMMISSIONED REPOSITORIES OF UNITARY ENTERPRISE «EKORES» TAKING INTO ACCOUNT THE RESULTS OF THEIR COMPREHENSIVE ENGINEERING AND RADIATION SURVEY

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The stocks of radioactive waste activity in the mothballed and decommissioned repositories of Unitary Enterprise «Ekores» have been estimated based on the results of their comprehensive engineering and radiation survey.

Keywords: the stock of radioactive waste activity, comprehensive engineering and radiation examination, shallow ground radioactive waste repositories, field gamma spectrometry method.

Introduction. Today special enterprise for radioactive waste management, Unitary Enterprise «Ekores» (hereinafter – «Ekores») is a complex radiation-hazardous facility, on the site of which there are:

two shallow ground radioactive waste repositories of the «first generation» buried type (operation from 1963 to 1978, in 1979 they were mothballed);

two shallow ground radioactive waste repositories of the «second generation» buried type (underground monolithic blocks, each consisting of 8 tanks, operation from 1978 to 2013, now one of them is mothballed, the second is at the stage of decommissioning), in which there are four mothballed wells (2 in each) for the placement of spent sealed radionuclide sources (hereinafter –SRS);

repository for spent SRS with 11 well-type containers (in operation since 2003);

ground-type conditioned solid radioactive waste repository (in operation since 2013);

radioactive waste reprocessing facility with laboratories (in operation since 2013).

In the initial period, radioactive waste was disposed of in shallow ground repositories of a trench type, and then – in special structures of a buried type, which are monolithic structures (tanks) made of reinforced concrete. In the CIS and Eastern Europe similar structures, that are carried out according to the standard design of the Moscow Design Institute, are referred to as shallow ground repositories of the «Radon» type. Radioactive waste was placed in repositories in the manufacturer's packaging without prior sorting and processing.

Since 1997, in order to bring the repository into a state that meets modern safety requirements, its reconstruction is carried out. As a result of the reconstruction project of «Ekores», the construction and commissioning of the radioactive waste processing facility and the new radioactive waste repository for new radioactive waste entering the enterprise were completed in 2013, that allows receiving radioactive waste (solid and liquid), their reprocessing and conditioning, as well as long-term storage of solid conditioned radioactive waste at a level that meets current requirements. The existing capacities of «Ecores» will ensure storage of radioactive waste generated in organizations of the Republic until about 2030. However, further storage of radioactive waste in the shallow ground repositories of the "first" and "second generation" may cause a deterioration of the radioecological situation in the region [1].

In 2019 in order to determine the objective level of radiation and environmental safety, as well as obtain initial data for the development of a project for radioactive waste extraction Stock company «Logistics Center of NFC» (Russian Federation) together with Stock company «PDC UGR», Limited liability company AP «KVARK», FSUE «RADON» (Russian Federation) carried out works on a comprehensive engineering and radiation survey (hereinafter – CERS) of mothballed and decommissioned «Ekores» repositories [2].

The state scientific institution «JIPNR – Sosny» of NAS of Belarus carried out scientific and methodological support of these works on CERS.

One of the tasks of CERS was determination of the total and specific activity of radionuclides in the repositories, that is one of the most important parameters necessary for estimation of the radiation situation at the industrial site, in the sanitary protection zone and the monitoring zone of radiation facilities, as well as estimation of the potential danger of shallow ground radioactive waste repositories [2,3].

The specifics of the so-called "historical" radioactive waste repositories is the lack of reliable information about the characteristics of the radioactive waste placed in it, including the specific activity of the radioactive waste (at best, the information about the radioactive waste is limited to information about the total alpha and beta activity and the radionuclide composition of the radioactive waste). The specific activity of radionuclides, as a rule, is determined by an expert method based on knowledge of the technologies that were used at different time periods [4].

The aim of this work is to estimate the stocks of radioactive waste activity in mothballed and decommissioned «Ekores» repositories taking into account the results of the CERS.

Information about radioactive waste buried in the shallow ground radioactive waste repositories of the "first generation" buried type

From 1963 to 1979 on the territory of «Ekores», radioactive waste was buried in trench-type repositories (canyon No. 1 and canyon No. 2). In this case, the spent SRS were placed together with the rest of the radioactive waste nomenclature. Until 1998, reliable data on the entrance and disposal of radioactive waste and SRS in tanks were absent.

During the filling of canyons, the characteristics of radioactive waste in the certificates were not given fully enough. For this reason, it is difficult to establish a reliable picture of what is in these repositories.

At that time the main sources of radioactive waste formation were the Institute of Nuclear Energy of the Academy of Sciences of the BSSR with the IRT-2000 reactor and the V.I. Lenin Minsk Instrument-Making Plant, that produced dosimetric instruments and special-purpose equipment for the Ministry of Defense and the Navy. In canyons No. 1 and No. 2, a large volume of building materials contaminated with ^{226}Ra, cleaning materials (cotton, rags, paper), contaminated with residual phosphorus residues based on ^{226}Ra, light-weight peeling, are buried; bubblers with residues of radium salt are also buried.

The bulk of the spent SRS were sources for gamma-ray inspection based on ^{152}Ir, ^{170}Tm, ^{75}Se, which were mainly disposed of in improvised containers. Most of the radioisotope technological control devices were buried entirely in the form of a block of gamma sources without preliminary discharge. Medical sources were also buried – the head of a cobalt gun with a source, applicators and needles for gamma therapy.

In 1998, in the MS Access-97 database management system a computer database was created with special software applications for solid radioactive waste and spent SRS buried in «Ekores» repositories and wells in order to improve the monitoring system for the life cycle of radioactive sources and substances. Simultaneously with the data bank, a system for automating the accounting of radioactive waste was created. The initial data for the creation of a data bank were the primary documents (protocols) for the entrance of radioactive waste and SRS at «Ekores». In total, more than 10,000 entries were processed with the participation of specialists from the State scientific institution «JIPNR – Sosny».

The computer database contains information on the entrance and disposal of radioactive waste and SIR for the entire period of operation of the «Ekores» repositories. Database data is differentiated by:

burial date;

the location (wells, mothballed burial places, containers in existing repositories with their numbers, storage in protective containers, etc.);

size and type of activity (neutron, gamma, beta, alpha sources, isotopic composition);

types and conditions of waste (spent SRS, plastic, glass, metal, rags, paper, etc.).

Special software applications make it possible to recalculate the activity of wastes at any given date, determine their isotopic composition, differentiate quantitative characteristics at the place of waste disposal, etc. The created database allows us to make an accurate analysis of the nomenclature of buried solid radioactive waste and SRS with a detailed definition of quantitative characteristics to develop recommendations for the extraction and recycling of waste from existing repositories.

The quantitative characteristics of radioactive waste located in mothballed canyons No. 1 and No. 2, refined based on the use of information from a computer database, are presented in Tables 1 and 2. In total, 123,484 kg of solid radioactive waste with total activity of $1{,}08 \cdot 10^{14}$ Bq are buried in canyons No. 1 and No. 2 of «Ekores».

Table 1 – Characteristics of the radioactive waste placed in the mothballed canyon No. 1 (as of the time of disposal)

№ п/п	Radioactive waste isotope composition	Half-life, years	Activity stock in repository, Bq	Radioactive waste specific activity in repository, Bq/м^3	Potential waste hazard time, years
1	^{14}C	5730,0	$3{,}7 \cdot 10^5$	$1{,}64 \cdot 10^3$	0
2	^{45}Ca	0,449	$3{,}7 \cdot 10^8$	$1{,}64 \cdot 10^6$	1,36
3	^{36}Cl	$3{,}01 \cdot 10^5$	$5{,}6 \cdot 10^8$	$2{,}49 \cdot 10^6$	$1{,}22 \cdot 10^6$
4	^{60}Co	5,271	$5{,}1 \cdot 10^{12}$	$2{,}27 \cdot 10^{10}$	100,6
5	^{137}Cs	30,17	$1{,}2 \cdot 10^{12}$	$5{,}3 \cdot 10^9$	573,8
6	^{3}H	12,28	$5{,}6 \cdot 10^{12}$	$2{,}5 \cdot 10^{10}$	143,3
7	^{192}Ir	0,2023	$5{,}6 \cdot 10^{12}$	$2{,}49 \cdot 10^{10}$	3,63
8	^{147}Pm	2,62	$2{,}2 \cdot 10^8$	$9{,}8 \cdot 10^5$	2,32
9	^{210}Po	0,379	$3{,}37 \cdot 10^{10}$	$1{,}5 \cdot 10^8$	7,7
10	^{239}Pu	24313,0	$1{,}1 \cdot 10^{11}$	$4{,}92 \cdot 10^8$	$4{,}8 \cdot 10^5$
11	^{226}Ra	1608,0	$4{,}9 \cdot 10^{11}$	$2{,}19 \cdot 10^9$	$3{,}55 \cdot 10^4$
12	^{75}Se	0,328	$1{,}2 \cdot 10^{10}$	$5{,}3 \cdot 10^7$	3,27
13	^{90}Sr	28,6	$1{,}5 \cdot 10^{10}$	$6{,}7 \cdot 10^7$	500
14	^{204}Tl	3,784	$2{,}2 \cdot 10^9$	$9{,}8 \cdot 10^6$	24
15	^{170}Tm	0,325	$1{,}7 \cdot 10^{12}$	$7{,}6 \cdot 10^9$	5,23
16	Mixed radioactive waste		$2{,}6 \cdot 10^{12}$	$1{,}15 \cdot 10^{10}$	
17	Composition is not determined		$1{,}9 \cdot 10^{10}$	$8{,}44 \cdot 10^7$	
	TOTAL		$8{,}214 \cdot 10^{12}$		

Table 2 – Characteristics of the radioactive waste placed in the mothballed canyon No. 2 (as of the time of disposal)

№ п/п	Isotope composition	Half-life, years	Activity stock in repository, Bq	Radioactive waste specific activity in repository, Bq/м^3	Potential waste hazard time, years
1	^{110m}Ag	0,70·	$7{,}4 \cdot 10^5$	$3{,}29 \cdot 10^3$	0
2	^{133}Ba	10,535	$2{,}2 \cdot 10^8$	$9{,}8 \cdot 10^5$	35,8
3	^{14}C	5730,0	$4{,}3 \cdot 10^{10}$	$1{,}9 \cdot 10^8$	$5{,}52 \cdot 10^4$

4	^{57}Co	0,745	$1,3·10^{7}$	$5,8·10^{4}$	0
5	^{60}Co	5,271	$2,6·10^{13}$	$1,16·10^{11}$	113
6	^{134}Cs	2,062	$1,9·10^{8}$	$8,4·10^{5}$	14,1
7	^{137}Cs	30,17	$1,6·10^{13}$	$7,1·10^{10}$	687
8	^{3}H	12,28	$2,6·10^{12}$	$1,16·10^{10}$	130
9	^{192}Ir	0,2023	$2,8·10^{13}$	$1,24·10^{11}$	4,1
10	^{32}P	0,0391	$6,7·10^{9}$	$2,98·10^{7}$	0,352
11	^{147}Pm	2,62	$1,6·10^{10}$	$7,1·10^{7}$	18,5
12	^{210}Po	0,379	$3,7·10^{9}$	$1,64·10^{7}$	6,47
13	^{238}Pu	87,75	$2,57·10^{8}$	$1,14·10^{6}$	956
14	^{239}Pu	24313,0	$8,9·10^{10}$	$3,96·10^{8}$	$4,7·10^{5}$
15	^{226}Ra	1608,0	$5,9·10^{10}$	$2,62·10^{8}$	$3,06·10^{4}$
16	^{35}S	0,24	$1,1·10^{10}$	$4,89·10^{7}$	1,31
17	^{124}Sb	0,164	$2,5·10^{10}$	$1,1·10^{8}$	1,8
18	^{75}Se	0,328	$3,2·10^{12}$	$1,42·10^{10}$	5,9
19	^{119m}Sn	0,802	$1,2·10^{6}$	$5,33·10^{3}$	0
20	^{90}Sr	28,6	$3,2·10^{11}$	$1,42·10^{9}$	626
21	^{232}Th	$1,4·10^{10}$	$3,7·10^{6}$	$1,64·10^{4}$	$6,7·10^{10}$
22	^{204}Tl	3,784	$1,8·10^{9}$	$8·10^{6}$	22,9
23	^{170}Tm	0,352	$1,8·10^{13}$	$8·10^{10}$	6,86
24	^{65}Zn	0,668	$3,5·10^{11}$	$1,564·10^{9}$	10,3
25	Mixed radioactive waste		$4,5·10^{12}$	$2·10^{10}$	
26	Not determined		$3,4·10^{11}$	$1,51·10^{9}$	
	TOTAL		$9,95·10^{13}$	$4,42·10^{11}$	

Information about radioactive waste buried in the shallow ground radioactive waste repositories of the "second generation" buried type

Until 1998, there were no reliable data on the entrance and disposal of radioactive waste and SRS in the repository tanks No. 1 and No. 2 for the entire period of operation since 1979, their quantity and nomenclature. The quantitative characteristics of radioactive waste and SRS buried at «Ekores» between 1963 and 1995 were approximate and, it is very significant, that there was no data on the isotopic composition of radioactive waste and SRS, and activity was estimated based on certificate data for the time of the burial of the waste lot.

The radioactive waste loaded in the repository tanks No. 1 and No. 2 of «Ekores» are characterized by great diversity. The entire array of contents of repository cells can be represented as consisting of the following types of radioactive waste, differing in the source material, the characteristic dimensions of individual units, and the method of containerization:

- radioactively contaminated consumables (rags, cover-up, personal protective equipment, etc.);
- bulk radioactive waste (furnace cinder, soil, soil samples, cleanings from hot chambers);
- spent SRS: long sources of γ-radiation with ^{60}Co isotopes, blocks of γ-sources with various radioisotopes, β-sources, radioactive smoke detectors of premises, etc.;
- biowaste (corpses of experimental animals, underlying materials, radioactive solutions ampoules);
- small-sized solid metallic and nonmetallic radioactive waste (elements of metal structures, pipelines, plastic parts, laboratory chemical glassware);
- waste of Chernobyl origin (mainly household items);

- large-sized metal radioactive waste (reactor vessel with bioprotection and structural elements of the transportable NPP «Pamir-630D», large-sized facility equipment, 200-liter metal barrels with cemented liquid waste).

The allocation of individual cells for the disposal of one type of radioactive waste until 1999 was not practiced. The sequence of loading tank cells was determined in the established order: at the beginning, the longest cells were filled, and lastly – the nearest cells. During loading, the radioactive waste lot was not sorted by activity level, and each successive cell was loaded as the radioactive waste entered. An inventory of radioactive waste buried before 1992 was absent.

In 2000, repository tank No. 1 was full. Radioactive waste was filled with an inert material (sand) after the cells of the repository tanks were fully loaded. By now, repository No. 1 has been mothballed without dismantling the protective ground structure.

Repository tank No. 2 was filled from October 1992 to 2013. Currently there are: a detailed inventory of its contents in the database; cell systematization of the characteristics of radioactive waste buried in this tank; information was collected on the characteristics of the radioactive waste buried in the tank, whose attachment to any of the cells is not documented.

Sand filling the filled cells of repository tank No. 2 was not performed. The exception is cells No. 1 and 8, that, after loading, were concreted. Cells of repositoris No. 1 and 2 are closed with concrete slabs of 20 cm thick. The isotopic composition of radioactive waste buried in these repositories varies significantly.

An enlarged systematization of information on loading repository cells by type of radioactive waste for repositories No. 1 and No. 2 is presented in tables 3 and 4, respectively.

Table 3 – Brief description of archival information on radioactive waste burial in cells of repository No. 1

Cell No.1 Radioactive waste burial was carried out before 1986. Presumably it was mainly small-sized solid radioactive waste and consumables.	**Cell No. 8** It was filled in 1986 - 1988 with wastes of Chernobyl origin (clothing, military uniforms, household items, etc.).
Cell No. 2 Similar to cell No. 1.	**Cell No. 7** It was filled in 1986 - 1988 with wastes of Chernobyl origin (clothing, military uniforms, household items, etc.).
Cell No. 3 Similar to cell No. 1.	**Cell No. 6** There is no reliable information on the loaded radioactive waste.
Cell No. 4 Burial of small and large radioactive waste - metal structures of the transportable NPP «Pamir-630D», (turbine-generating unit).	**Cell No. 5** There is no reliable information on the loaded radioactive waste.

Table 4 – Brief description of archival information on radioactive waste burial in cells of repository No. 2

Cell No. 1 It is divided into two compartments, currently not in operation and concreted. It contains a diverse nomenclature of radioactive waste and SRS.	**Cell No. 8** It was loaded in the post-Chernobyl period with contaminated clothing, synthetic wrapping material, rags, etc. It is completely filled, paved with asphalt. Under stove 8-4, the burial of small lots of control sources was organized.

Cell No. 2 Basically, SRS were buried here (blocks of gamma-ray sources, extended sources, sources in containers, etc.), due to the availability of free space, temporary storage of SIR was carried out.	**Cell No. 7** It is almost full, contains significant amounts of contaminated consumables.
Cell No. 3 By the nature of burials - the same as in cell No. 2; a large barrel – a special container for alpha sources – is additionally placed here.	**Cell No. 6** In the lower part – mainly furnace slag containing radium salts, higher in volume – biowaste, extended sources, cemented bottles with liquid radioactive waste, consumables, etc.
Cell No. 4 Radioactive waste of CJSC «Isotope technologies».	**Cell No. 5** The reactor block of the transportable NPP «Pamir-630D» with neutron sources and a few small lots of radioactive waste and SRS were buried here.

The quantitative characteristics of radioactive waste located in mothballed repositories No. 1 and No. 2, updated based on the use of information from a computer database, are presented in tables 5 and 6. The total activity of radioactive waste loaded into repositories No. 1 and No. 2 is $9{,}175\cdot10^{15}$ Bq.

Table 5 – Characteristics of radioactive waste disposed of in mothballed repository tanks No. 1 under the assumption of a uniform homogeneous distribution of the activity of radioisotopes in volume (at the time the radioactive waste enters the «Ekores»).

№ п/п	Isotope composition	Half-life, years	Activity stock in repository, Bq	Radioactive waste specific activity in repository, Bq/м^{3*}	Potential waste hazard time, years
1	^{241}Am	432,2	$3{,}37\cdot10^{10}$	$4{,}1\cdot10^{7}$	$6{,}86\cdot10^{3}$
2	^{133}Ba	10,7	$3{,}40\cdot10^{7}$	$4{,}1\cdot10^{4}$	0
3	^{207}Bi	38	$3{,}7\cdot10^{8}$	$4{,}5\cdot10^{5}$	77,3
4	^{14}C	5730,0	$4{,}37\cdot10^{9}$	$5{,}3\cdot10^{6}$	$2{,}56\cdot10^{4}$
5	^{144}Ce	0,778	$3{,}7\cdot10^{10}$	$4{,}5\cdot10^{7}$	8,33
6	^{57}Co	0,745	$3{,}7\cdot10^{12}$	$4{,}5\cdot10^{9}$	9,49
7	^{60}Co	5,271	$5{,}22\cdot10^{13}$	$6{,}4\cdot10^{10}$	109
8	^{51}Cr	0,076	$5{,}0\cdot10^{8}$	$6{,}1\cdot10^{5}$	0
9	^{134}Cs	2,06	$3{,}7\cdot10^{6}$	$4{,}5\cdot10^{3}$	0
10	^{137}Cs	30,17	$1{,}65\cdot10^{14}$	$2{,}0\cdot10^{11}$	732
11	^{152}Eu	13,2	$2{,}78\cdot10^{12}$	$3{,}4\cdot10^{9}$	199
12	^{55}Fe	2,68	$5{,}55\cdot10^{9}$	$6{,}8\cdot10^{6}$	10,8
13	^{153}Gd	0,663	$3{,}7\cdot10^{8}$	$4{,}5\cdot10^{5}$	0
14	^{3}H	12,28	$3{,}77\cdot10^{12}$	$4{,}6\cdot10^{9}$	113
15	^{192}Ir	0,202	2,45·1014	3,0·1011	4,35
16	^{85}Kr	10,72	1,11·109	1,4·106	
17	^{54}Mn	0,857	3,7·109	4,5·106	3,85
18	^{22}Na	2,6	5,14·108	6,3·105	10,1
19	^{63}Ni	96	4,63·105	5,6·102	0
20	^{32}P	0,039	$4{,}55\cdot10^{8}$	$5{,}6\cdot10^{5}$	0,13
21	^{147}Pm	2,62	$7{,}84\cdot10^{8}$	$9{,}6\cdot10^{5}$	2,25
22	^{210}Po	0,379	$1{,}85\cdot10^{10}$	$2{,}3\cdot10^{7}$	6,65
23	^{210}Po +Be	0,379	$1{,}8\cdot10^{11}$	$2{,}2\cdot10^{8}$	7,89
24	^{238}Pu	87,75	$9{,}95\cdot10^{11}$	$12{,}1\cdot10^{8}$	$1{,}84\cdot10^{3}$

25	^{238}Pu +Be	87,75	$2{,}03 \cdot 10^{12}$	$2{,}5 \cdot 10^{9}$	$1{,}93 \cdot 10^{3}$
26	^{239}Pu	24313,0	$7{,}53 \cdot 10^{11}$	$9{,}2 \cdot 10^{8}$	$5{,}02 \cdot 10^{5}$
27	^{226}Ra	1608,0	$1{,}2 \cdot 10^{12}$	$1{,}5 \cdot 10^{9}$	$3{,}46 \cdot 10^{4}$
28	^{124}Sb	0,165	$1{,}25 \cdot 10^{12}$	$1{,}5 \cdot 10^{9}$	2,98
29	^{75}Se	0,329	$1{,}32 \cdot 10^{13}$	$1{,}6 \cdot 10^{10}$	7,08
30	^{119m}Sn	0,803	$1{,}40 \cdot 10^{9}$	$1{,}7 \cdot 10^{6}$	1,65
31	^{90}Sr	28,6	$1{,}05 \cdot 10^{12}$	$1{,}3 \cdot 10^{9}$	622
32	^{204}Tl	3,784	$8{,}88 \cdot 10^{10}$	$10{,}8 \cdot 10^{7}$	37
33	^{170}Tm	0,353	$4{,}37 \cdot 10^{13}$	$5{,}3 \cdot 10^{10}$	6,67
34	^{238}U depleted	$4{,}47\ 10^{9}$	$3{,}7 \cdot 10^{8}$	$4{,}5 \cdot 10^{5}$	$3{,}21 \cdot 10^{10}$
35	^{88}Y	0,292	$3{,}7 \cdot 10^{8}$	$4{,}5 \cdot 10^{5}$	0,59
36	^{65}Zn	0,668	$2{,}51 \cdot 10^{10}$	$3{,}1 \cdot 10^{7}$	6,51
37	Mixed radioactive waste		$1{,}27 \cdot 10^{14}$	$1{,}6 \cdot 10^{11}$	
38	Radioactive waste composition is not determined		$5{,}4 \cdot 10^{12}$	$6{,}6 \cdot 10^{9}$	
39	Special material		$3{,}52 \cdot 10^{13}$	$4{,}3 \cdot 10^{10}$	
	TOTAL		$7{,}05 \cdot 10^{14}$		

Table 6 – Characteristics of radioactive waste disposed of in filled repository tanks No. 2 under the assumption of a uniform homogeneous distribution of the activity of radioisotopes in volume (at the time the radioactive waste enters the «Ekores»)

№ п/п	Isotope composition	Half-life, years	Activity stock in repository, Bq	Radioactive waste specific activity in repository, Bq/м^{3*}	Potential waste hazard time, years
1	^{110m}Ag	0,685	$1{,}32 \cdot 10^{8}$	$1{,}79 \cdot 10^{5}$	1,26
2	^{241}Am	432,2	$2{,}41 \cdot 10^{11}$	$3{,}27 \cdot 10^{8}$	$8{,}15 \cdot 10^{3}$
3	^{199}Au	$8{,}6 \cdot 10^{-3}$	$7{,}40 \cdot 10^{4}$	$1{,}00 \cdot 10^{2}$	0
4	^{133}Ba	10,7	$5{,}59 \cdot 10^{7}$	$7{,}58 \cdot 10^{4}$	0
5	^{14}C	5730,0	$3{,}71 \cdot 10^{10}$	$5{,}03 \cdot 10^{7}$	$4{,}42 \cdot 10^{4}$
6	^{45}Ca	0,449	$1{,}85 \cdot 10^{6}$	$2{,}51 \cdot 10^{3}$	1,64
7	^{109}Cd	1,27	$2{,}49 \cdot 10^{10}$	$3{,}37 \cdot 10^{7}$	$1{,}56 \cdot 10^{1}$
8	^{144}Ce	0,778	$3{,}85 \cdot 10^{9}$	$5{,}22 \cdot 10^{6}$	5,91
9	^{36}Cl	$3{,}01 \cdot 10^{5}$	$1{,}20 \cdot 10^{8}$	$1{,}63 \cdot 10^{5}$	$3{,}61 \cdot 10^{4}$
10	^{244}Cm	18,1	$4{,}00 \cdot 10^{3}$	5,42	0
11	^{57}Co	0,745	$7{,}51 \cdot 10^{10}$	$1{,}02 \cdot 10^{8}$	5,42
12	^{60}Co	5,271	$3{,}00 \cdot 10^{15}$	$4{,}07 \cdot 10^{12}$	$1{,}40 \cdot 10^{2}$
13	^{51}Cr	0,076	$1{,}47 \cdot 10^{11}$	$1{,}99 \cdot 10^{8}$	$4{,}37 \cdot 10^{-1}$
14	^{134}Cs	2,06	$6{,}48 \cdot 10^{8}$	$8{,}78 \cdot 10^{5}$	$1{,}42 \cdot 10^{1}$
15	^{137}Cs	30,17	$4{,}90 \cdot 10^{15}$	$6{,}64 \cdot 10^{12}$	$8{,}84 \cdot 10^{2}$
16	^{152}Eu	13,2	$1{,}73 \cdot 10^{5}$	$2{,}34 \cdot 10^{2}$	0
17	^{55}Fe	2,68	$8{,}25 \cdot 10^{10}$	$1{,}12 \cdot 10^{8}$	$2{,}16 \cdot 10^{1}$
18	^{153}Gd	0,663	$4{,}40 \cdot 10^{8}$	$5{,}96 \cdot 10^{5}$	$1{,}49 \cdot 10^{-1}$
19	^{3}H	12,28	$6{,}18 \cdot 10^{13}$	$8{,}37 \cdot 10^{10}$	$1{,}65 \cdot 10^{2}$
20	^{203}Hg	0,128	$7{,}03 \cdot 10^{10}$	$9{,}53 \cdot 10^{7}$	1,75
21	^{125}I	0,162	$4{,}75 \cdot 10^{10}$	$6{,}44 \cdot 10^{7}$	2,07
22	^{131}I	0,022	$1{,}17 \cdot 10^{9}$	$1{,}56 \cdot 10^{6}$	0,18
23	^{192}Ir	0,202	$4{,}39 \cdot 10^{14}$	$5{,}95 \cdot 10^{11}$	4,55
24	^{40}K	$1{,}28 \cdot 10^{9}$	$2{,}41 \cdot 10^{4}$	$3{,}27 \cdot 10^{1}$	0
25	^{85}Kr	10,72	$2{,}02 \cdot 10^{10}$	$2{,}74 \cdot 10^{7}$	
26	^{54}Mn	0,857	$1{,}01 \cdot 10^{9}$	$1{,}37 \cdot 10^{6}$	2,38
27	^{99}Mo	0,0075	$7{,}36 \cdot 10^{10}$	$9{,}97 \cdot 10^{7}$	$6{,}57 \cdot 10^{-2}$
28	^{22}Na	2,6	$9{,}98 \cdot 10^{7}$	$1{,}35 \cdot 10^{5}$	4,29

29	^{63}Ni	96	$8,65\cdot10^{10}$	$1,17\cdot10^{8}$	$6,70\cdot10^{2}$
30	^{32}P	0,039	$1,04\cdot10^{4}$	$1,41\cdot10^{1}$	0
31	^{147}Pm	2,62	$4,74\cdot10^{9}$	$6,42\cdot10^{6}$	9,43
32	^{210}Po	0,379	$1,85\cdot10^{10}$	$2,51\cdot10^{7}$	6,70
33	^{236}Pu	2,85	$2,03\cdot10^{2}$	$2,75\cdot10^{-1}$	0
34	^{238}Pu	87,75	$1,03\cdot10^{12}$	$1,40\cdot10^{9}$	$1,86\cdot10^{3}$
35	^{238}Pu +Be	87,75	$8,99\cdot10^{10}$	$1,22\cdot10^{8}$	$1,55\cdot10^{3}$
36	^{238} Pu B	87,75	$1,55\cdot10^{13}$	$2,10\cdot10^{10}$	$2,20\cdot10^{3}$
37	^{239}Pu	24313,0	$2,14\cdot10^{12}$	$2,90\cdot10^{9}$	$5,42\cdot10^{5}$
38	^{242}Pu	$3,76\cdot10^{5}$	$2,15\cdot10^{2}$	$2,91\cdot10^{-1}$	0
39	^{226}Ra	1608,0	$1,25\cdot10^{12}$	$1,69\cdot10^{9}$	$3,49\cdot10^{4}$
40	^{103}Ru	0,108	$9,62\cdot10^{4}$	$1,30\cdot10^{2}$	0
41	^{106}Ru	1,01	$5,88\cdot10^{9}$	$7,97\cdot10^{6}$	8,73
42	^{125}Sb	2,77	$2,02\cdot10^{7}$	$2,74\cdot10^{4}$	0
43	^{75}Se	0,33	$7,29\cdot10^{12}$	$9,88\cdot10^{9}$	5,78
44	^{113}Sn	0,315	$8,96\cdot10^{4}$	$1,21\cdot10^{2}$	0
45	^{119m}Sn	0,803	$1,17\cdot10^{9}$	$1,59\cdot10^{6}$	1,57
46	^{90}Sr	28,6	$1,20\cdot10^{12}$	$1,63\cdot10^{9}$	$6,31\cdot10^{2}$
47	^{232}Th	$1,4\ 10^{10}$	$2,01\cdot10^{6}$	$2,72\cdot10^{3}$	$7,71\cdot10^{10}$
48	^{204}Tl	3,784	$3,10\cdot10^{9}$	$4,20\cdot10^{6}$	$1,94\cdot10^{1}$
49	^{170}Tm	0,353	$2,34\cdot10^{11}$	$3,17\cdot10^{8}$	4,06
50	^{238}U depleted	$4,47\ 10^{9}$	$1,51\cdot10^{9}$	$2,05\cdot10^{6}$	$4,19\cdot10^{10}$
51	^{88}Y	0,293	$2,00\cdot10^{8}$	$2,71\cdot10^{5}$	$3,81\cdot10^{-1}$
52	^{65}Zn	0,668	$1,54\cdot10^{5}$	$2,09\cdot10^{2}$	0
53	^{95}Zr	0,175	$3,00\cdot10^{6}$	$4,07\cdot10^{3}$	0
54	Radioactive waste composition is not determined		$2,19\cdot10^{10}$	$2,97\cdot10^{7}$	
55	Mixed radioactive waste		$3,75\cdot10^{13}$	$5,08\cdot10^{10}$	
56	Special material		0		
	TOTAL		$8,47\cdot10^{15}$		

Well repository type inv. No. 369, No. 422 as part of repository No. 1 began to operate in the early 1980s. In accordance with the data of archival records in the repository of spent SRS, inv. number 369, 3578 sources were buried with a total activity of $44,29\cdot10^{12}$ Bq. The main contribution to the activity is made by ^{137}Cs ($34,74\cdot10^{12}$ Bq). Due to an emergency during loading, the technological channel of the repository, inv. No. 369 was covered up with metal shot; reception of sealed radionuclide sources was discontinued. The repository of SRS, inv.No 422 since 1982 was used mainly for the disposal of neutron sources. Information on the number of buried neutron sources has not been preserved. At the same time, 93 sources of ^{226}Ra with an activity of $3,7\cdot10^{9}$ Bq were placed in this repository.

Well type repository inv. No. 423, No. 423 as part of repository No. 2 have been in operation since the early 1990s and were used mainly for storing gamma sources. In accordance with the data of archival records in the repository of spent SRS, inv. No. 423, 7198 sources with a total activity of $2,84\cdot10^{15}$ Bq were buried. The main contribution to the activity is made by ^{137}Cs ($2,81\cdot10^{15}$ Bq). In the repository of spent SRS, inv. No. 424, 66 sources of ^{60}Co and ^{137}Cs with a total activity of $56,98\cdot10^{13}$ Bq were buried. The main contribution to the activity is made by ^{137}Cs sources ($56,98\cdot10^{13}$ Bq).

Estimation of the radionuclide composition and activity of radioactive waste disposed at «Ekores» mothballed and decommissioned repositories, taking into account the results of CERS

During the CERS work on the «Ekores» repositories that were mothballed and decommissioned, the Stock company «Logistics Center of NFC» specialists using the field spectrometry method using the ISOCS complex, investigated the radionuclide composition and estimated the activity of radionuclides in the repositories. For field gamma spectrometric measurements, the «Methodology for measuring the activity (specific activity) of radionuclides in closed containers with compacted solid or solidified radioactive waste using a CANBERRA semiconductor gamma spectrometer with ISOCS software» was used.

Investigation of the radionuclide composition and estimation of the radionuclides activity in the repositories were carried out sequentially throughout the volume of repositories, so that the investigated and simulated areas intersected edges with each other and went beyond the limits of interest. This approach made it possible to estimate the radiation parameters of the entire repository volume and to avoid accidental loss of required information due to the presence of uninvestigated parts of them.

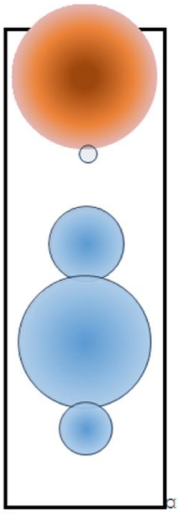
In the trench-type repositories (Canyon No. 1 and Canyon No. 2), five measurements were taken at equal distances (3 m) along the longitudinal axis of the repository. To ensure spectrometric equipment access to their floors, pits of 1.5 m were dug along the longitudinal axis along the entire length of the repositories in the embankment (Figure 1). At repositories No. 1 and No. 2, all cells were individually examined sequentially (eight in each of the repositories). Measurements were taken through the geometric center of the cell overlap surface. Access to the floors of repositories No. 1 and No. 2 is free, that did not require preparatory work for their gamma-spectrometric examination (Figure 2).

Figure 1 – Measurements on the overlap of canyons No. 1 and No. 2

Figure 2 – Measurements on the overlap of repositories No. 1 and No. 2

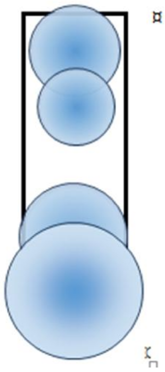
The filling level of all radioactive waste repositories in the segments models of repository and cell was taken based on the results of a previous survey of the degree of filling the repositories (repository compartments) and measuring the equivalent dose rate distribution during logging in drilled vertical penetrations. The active layer of radioactive waste in the repositories during the calculations was modeled by two levels – the distribution of activities and the results of the dosimetric examination of the side walls of the repositories.

Schematically diagrams of the distribution of activity of the main dose-generating radionuclides along the length of the repositories are presented in Figures 3-6. [2].



Nuclide	Activity, Bq
^{226}Ra	$4,8 \cdot 10^{11}$
^{137}Cs	$1,5 \cdot 10^{10}$
^{137}Cs	$6,6 \cdot 10^{10}$
^{137}Cs	$3,26 \cdot 10^{11}$
^{137}Cs	$4,4 \cdot 10^{10}$

Figure 3 – activity distribution diagram of the main dose-generating radionuclides along the length of canyon No. 1



Nuclide	Activity, Bq
^{137}Cs	$3,6 \cdot 10^{11}$
^{137}Cs	$1,8 \cdot 10^{11}$
^{137}Cs	$1,6 \cdot 10^{6}$
^{137}Cs	$6,1 \cdot 10^{11}$
^{137}Cs ^{152}Eu	$18,4 \cdot 10^{10}$ $3,4 \cdot 10^{6}$

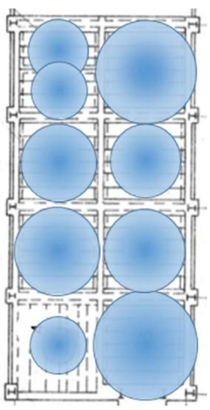
Figure 4– activity distribution diagram of the main dose-generating radionuclides along the length of canyon No. 2

The radionuclide composition of the "first generation" repositories (canyon No. 1 and No. 2) determined by direct gamma-spectrometric measurements mainly corresponds to the data of preserved archival records on the location in these radioactive waste repositories provided by the operating organization.

According to the results of gamma-ray field spectrometry, ^{226}Ra radionuclides (with a total activity of $4,8 \cdot 10^{11}$ Bq), mainly concentrated at a depth of 1.5 m, and ^{137}Cs (with a total activity of $4,5 \cdot 10^{11}$ Bq), mainly concentrated in the bottom of the store, were found. Determining factor is ^{137}Cs (total activity $2,96 \cdot 10^{12}$ Bq) in the entire volume of Canyon No. 2. The difference in the radionuclide composition is determined by the presence in the canyon No. 2 of a small amount of the ^{152}Eu isotope, that may be due to the lack of necessary records of the burial or secondary activation of its materials by neutrons from sources located inside the repository and not having the necessary protection.

The information received does not correspond to the data of the archival records on the location of radioactive waste in mothballed canyons No. 1 and No. 2 at the time of the «disposal», where a significantly larger range of radionuclides is reported, and the resulting total activity of radioactive waste in both repositories (canyon No. 1 – $9,3 \cdot 10^{11}$ Bq; canyon No. 2 – $2,96 \cdot 10^{12}$ Bq) turned out to be an order of magnitude less archival, shown in Tables 1, 2. The obtained deviations can be explained by the natural decrease in activity and the imperfection of the field spectrometry technique, that cannot take into account the activity of ionizing radiation sources enclosed in protective packaging.

sec	Nuclide	Activity, Bq
1.1	^{137}Cs	$4,1 \cdot 10^{12}$
1.2	^{137}Cs	$3,8 \cdot 10^{12}$
2	^{137}Cs	$5,9 \cdot 10^{12}$
3	^{137}Cs	$7,4 \cdot 10^{12}$
4	^{137}Cs	$3,7 \cdot 10^{12}$
5	^{137}Cs	$11,7 \cdot 10^{12}$
6	^{137}Cs	$6,8 \cdot 10^{12}$
7	^{137}Cs	$5,2 \cdot 10^{12}$
8	^{137}Cs ^{60}Co	$10,6 \cdot 10^{12}$ $4,5 \cdot 10^{10}$



Com-partment	Nuclide	Activity, Bq
2.1	^{137}Cs	$2,9 \cdot 10^{13}$
2.2	^{137}Cs ^{60}Co	$8,0 \cdot 10^{10}$ $2,9 \cdot 10^{9}$
2	^{137}Cs ^{60}Co	$3,0 \cdot 10^{10}$ $6,2 \cdot 10^{9}$
3	^{137}Cs ^{60}Co	$1,2 \cdot 10^{10}$ $4,7 \cdot 10^{7}$
4	^{137}Cs ^{60}Co	$0,7 \cdot 10^{10}$ $4,7 \cdot 10^{7}$
5	≤ MDA	-
6	^{137}Cs ^{60}Co ^{152}Eu	$36 \cdot 10^{10}$ $3,8 \cdot 10^{8}$ $8,0 \cdot 10^{8}$
7	^{137}Cs ^{60}Co	$6,4 \cdot 10^{9}$ $3,8 \cdot 10^{9}$
8	^{137}Cs	$2,4 \cdot 10^{10}$

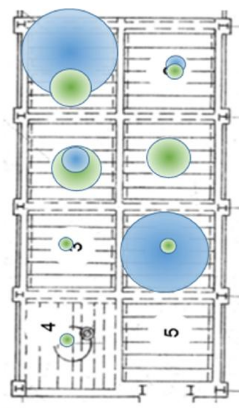


Figure 5 – activity distribution diagram of the main dose-generating radionuclides through the repository No. 1 compartments

Figure 6 – activity distribution diagram of the main dose-generating radionuclides through the repository No. 2 compartments

According to the results of gamma-ray field spectrometry, of the detected radionuclides, the determining factor is ^{137}Cs (with a total activity of $1{,}18 \cdot 10^{14}$ Bq) and ^{60}Co (with a total activity of $4{,}48 \cdot 10^{10}$ Bq) through the entire volume of repository No. 2. The main dose-generating radionuclides in repository No. 2 are ^{137}Cs, ^{60}Co (compartments No. 2, 3, 4, 6, 7, 8), ^{241}Am (compartment No. 2) and ^{152}Eu (compartment No. 6).

The information obtained does not correspond to the data of the archival records on the location of radioactive waste in the mothballed repositories No. 1 and No. 2 at the time of the «disposal», where a significantly larger nomenclature of radionuclides is reported, and the resulting total activity of the radioactive waste for both repositories (repository No. 1 – $1{,}18 \cdot 10^{14}$ Bq, repository No. 2 – $2{,}98 \cdot 10^{13}$ Bq) is slightly lower than the archival given in tables 5.6.

Table 7 presents expert estimates of the specific and total activities of radioactive waste located in the mothballed and decommissioned «Ekores» repositories taking into account the results of CERS [2]. Since the spent sealed radionuclide sources located in the well-type repository, inv. No. 369, were not conditioned due to the obstruction of the technological channel, it was not possible to determine their specific activity. It was also not possible to clarify data on the total activity of sources buried in a well-type repository, inv. No. 422, within the framework of the CERS.

Table 7 – Expert estimates of specific and total activities of radioactive waste contained in the examined «Ekores» repositories

Name of the facility	Total activity, Bq	Specific activity, Bq/kg
Canyon No. 1	$8{,}214 \cdot 10^{12}$	$8{,}214 \cdot 10^{10}$
Canyon No. 2	$9{,}95 \cdot 10^{13}$	$9{,}95 \cdot 10^{11}$
Repository No.1	$7{,}05 \cdot 10^{14}$	$7{,}05 \cdot 10^{12}$
Repository No. 2	$8{,}47 \cdot 10^{15}$	$8{,}47 \cdot 10^{13}$
Repository of the spent SRS, inv. No. 369	$44{,}29 \cdot 10^{12}$	Not determined
Repository of the spent SRS, inv. No. 422	$3{,}7 \cdot 10^{9}$	$3{,}7 \cdot 10^{7}$
Repository of the spent SRS, inv. No. 423	$2{,}84 \cdot 10^{15}$	$2{,}84 \cdot 10^{13}$
Repository of the spent SRS, inv. No. 424	$56{,}98 \cdot 10^{13}$	$56{,}98 \cdot 10^{11}$
Total	**$1{,}27 \cdot 10^{16}$**	

Thus, according to expert estimates, the total stock of radioactive waste activity in the mothballed and decommissioned «Ekores» repositories is $1{,}27 \cdot 10^{16}$ Bq.

It should be noted that in the above mentioned estimates of radioactive waste activities in «Ekores» repositories, based on archival data, the decay of radionuclides during the time after filling the repositories was not taken into account, since a significant proportion is radioactive waste of uncertain and mixed composition. This leads to an overestimation of activity ratings. At the same time, the incompleteness of the initial archival data leads to an underestimation, and, thus, the indicated errors are leveled to a certain extent.

Taking into account the results of the CERS and based on the analysis of archival data on the history of filling repositories, it can be concluded that upon decommissioning of «Ekores» repositories all possible types of waste will be generated: non-radioactive, very low-level, low-level, medium-active and high-level waste (table 8).

Table 8 – Expert estimates of distribution of volumes of radioactive waste disposed in the examined «Ekores» repositories by categories

Name of the facility	Distribution of radioactive waste volumes by categories, %			
	very low-level	low-level	medium-active	high-level
Canyon No. 1	60-65	30-35	7-10	–
Canyon No. 2	80-85	10-15	5-7	–
Repository No. 1	70-75	20-25	5-7	Less than 1
Repository No. 2	60-70	30-35	5-10	1-2
Repository of the spent SRS, inv. No. 369	–	–	–	100
Repository of the spent SRS, inv. No. 422	–	–	100	–
Repository of the spent SRS, inv. No. 423	–	–	–	100
Repository of the spent SRS, inv. No. 424	–	–	–	100

The following comparisons are indicative of the obtained estimate of the total stock of radioactive waste activity in the mothballed and decommissioned «Ekores» repositories ($1{,}27 \cdot 10^{16}$ Bq).

Chernobyl decontamination waste isolated at 86 disposal sites on the territory of the Republic of Belarus has a total activity of about $3{,}7 \cdot 10^{12}$ Bq, that is three orders of magnitude lower than in the considered «Ekores» repositories.

As of 2019, the total activity of ^{137}Cs radionuclides in the territory of 27.9 thousand km^2 , estimated on the basis of the data [7] on the contamination of the territory of the Republic of Belarus as a result of the Chernobyl accident, is about $6{,}2 \cdot 10^{15}$ Bq, that is, of the same order , as in the considered repositories. At the same time, the range of radionuclides in the «Ekores» repositories is much wider and is represented by more radiologically hazardous isotopes.

The given comparisons testify to the urgency of the problem of ensuring the radiation safety of the «Ekores» radioactive waste management company.

Conclusion

According to the results of the CERS of the mothballed and decommissioned «Ekores» repositories, it can be concluded that the used radiometric methods did not allow an objective estimation of the qualitative and quantitative composition of the radioactive waste contained in the chambers of the examined repositories. Estimation of the total and specific activity of buried radioactive waste can be obtained from archival data on the history of filling repositories or during the extraction and certification of radioactive waste. According to expert estimates, the total stock of radioactive waste activity in the mothballed and decommissioned «Ekores» repositories amounted to $1{,}27 \cdot 10^{16}$ Bq.

References

1. Zhemzhurov M.L. Republican radioactive waste repository: status and prospects / M.L. Zhemzhurov, V.V. Skurat. // Internatioanl Conference dedicated to the centenary of the birth of N.V. Timofeev-Resovsky: materials of the International Conference, Minsk, 17-18 october 2000 / A. D. Sakharov International Environmental Institute. – P. 18-20.

2. Technical report on the results of a comprehensive engineering and radiation examination of the mothballed and decommissioned radioactive waste repositories of the Unitary Enterprise «Ekores» / State Atomic Energy Corporation «Rosatom», Stock company «Logistics Center of NFC». – Moscow, 2019. –469 p.

3. Korenkov I.P. An integrated approach to estimating the potential hazard of shallow ground radioactive waste repositories / I.P. Korenkov [and others] // Hygiene and sanitation. – Vol. 95, edit. 2. – 2016. – P. 133–139.

4. Sharafutdinov, R.B. Potential hazard ranking of solid radioactive waste repositories of nuclear enterprises / R.B. Sharafutdinov [and others] // Nuclear and radiation safety. – No. 1. – 2010. – P. 10–15.

5. Belarus and Chernobyl: 33 years later: informational and analytical compilation / under the editorship of P.V. Nikolaenko; Department for the liquidation of the consequences of the disaster at the Chernobyl nuclear power plant of the Ministry of Emergency Situations of the Republic of Belarus.– Minsk: Information and Computing Center of the Ministry of Finance, 2019. –100 p.