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RADIOACTIVE CONTAMINATION OF GROUNDWATER AT WASTE DUMP SITES IN CHERNOBYL EXCLUSION ZONE

Results are presented of groundwater contamination survey of several waste dump sites in the 10-km zone of the Chernobyl NPP containing wastes from post-accident decontamination activities (e.g., "red forest" destroyed by extreme radiation levels in 1986). Groundwater sampling in the immediate vicinity of waste burials using Waterloo Profiler push-drill system carried out in July — August 2015 has shown that the main hazard is related to groundwater contamination by strontium-90. Strontium-90 concentrations in groundwater ranged for different waste burials from 1.1 to 17800 Bq/l significantly exceeding the permissible activity concentration in drinking water of 2 Bq/L. Concentrations of cesium-137 in groundwater varied from values below the detection limit (<0.04 Bq/l) to 0.6 Bq/l (thus lower than the permissible activity concentration in drinking water of 2 Bq/l). Sampling results revealed that levels of radioactive contamination of groundwater by strontium-90 at waste dump sites are relatively stable over the last two decades, which is consistent with the hypothesis of gradual dissolution of nuclear fuel particles in waste material, and release of radioactive contaminants to groundwater system. Lower levels of strotium-90 in groundwater were observed at "Neftebaza" waste dump site near the Pripyat Zaton surface water body, being likely caused by specific hydrogeological and geochemical conditions of this site (clayey soils; higher lateral groundwater seepage rates; reducing alkaline geochemical environment). The obtained data on radioactive contamination of groundwater in the immediate vicinity of waste burials with the help of the push-drill auger provide significantly higher levels of groundwater contamination in comparison to the data of the regime monitoring network of the Special State Enterprise "Ecocenter", which is responsible for radiation monitoring in the Chernobyl Exclusion zone. This confirms that the existing system of hydrogeological monitoring of the waste dump sites in the 10-km zone of the ChNPP requires further improvement and development.

Keywords: *Chernobyl accident; strontium-90; cesium-137; groundwater,; monitoring.*

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Introduction

One of the most important sources of radioactive contamination of groundwater in the Chernobyl exclusion zone are the so-called Radioactive Waste Temporary Storage Sites (RWTSS), established in 1987-88 during the decontamination of the territory adjacent to the Chernobyl Nuclear Power Plant (ChNPP) (Dzhepo et al., 1994; Bugai et al., 1996; Antropov et al., 2001). The RWTSS are composed of shallow unlined trenches and above ground "clamps" containing radioactively contaminated materials generated during decontamination (soil, vegetation remnants, construction garbage), which were covered from the top by a clean soil layer. In total, the decontamination area was about 12 km^2, while the total number of individual waste burials is about 800. The RWTSS were later sub-divided into sectors including the following ones: "Red Forest", "Yanov Station", "Staraya Stroybaza", "Novaya Stroybaza", "Neftebaza", "Sandy Plateau" and "Kopachi" (Antropov et al., 2001; Molitor et al., 2017). The main sources of radioactivity in waste dumps are micron-size nuclear fuel particles with the uranium oxide matrix, which have formed during the Chernobyl accident (Kashparov et al., 2003). These fuel particles gradually dissolve under influence of environmental factors and release radionuclides in mobile (ion-exchangeable) forms (Kashparov et al., 2019). Radioactive contaminants released from waste dumps infiltrate to the local unconfined aquifer composed of Quaternary sandy deposits. The upper part of the geological section at ChNPP site is composed of the fine-grained quartz sands of eolian genesis, which have a relatively high permeability (3-5 m/day) and low sorption capacity (cation exchange capacity of about 1–1.2 meq/100g). A detailed description of radiation conditions and hydrogeological conditions of RWTSS is provided in (Dzhepo et al., 1994; Antropov et al., 2001; Bugai et al., 2012a).

The existing system of groundwater monitoring of the Chernobyl exclusion zone, which is operated by the State Specialized Enterprise (SSE) "Ecocenter", does not allow to obtain accurate data on the radioactive contamination of groundwater in the immediate vicinity of waste burials at the RWTSS as siting of monitoring wells does not account for the layout of individual burials on terrain, and monitoring wells often have large 12 m long screens resulting in vertically-averaged groundwater samples (Dzhepo et al.,1998; Kireev et al., 2019). The contaminated groundwater emerging from RWTSS poses potential threat of contamination of Pripyat River, which receives subsurface flow from the ChNPP site.

The last systematic field surveys of radioactive contamination of groundwater at RWTSS were carried out within the framework of the "Polygon" research project in 1998-2000 (Institute of Geological Sciences, 2001). Subsequently, in 2000-2012, monitoring studies of radioactive contamination of groundwater were carried out at the single site only — at the international research site "Experimental Platform in Chernobyl" at the "Red Forest" RWTSS near trench no. 22-T (Van Meir et al., 2009; Bugai et al., 2012a). No purposeful groundwater contamination surveys have been carried out at other RWTSS. For some of RWTSS sectors, such as "Staraya Stroybaza" (which belongs to the most radioactively contaminated sites), no groundwater monitoring studies have been conducted during the entire post-Chernobyl accident period. Therefore, conducting the survey of radioactive contamination of groundwater in the RWTSS sectors in the near zone of ChNPP in order to assess radioactivity releases to the geo-environment was an urgent task.

In this article we present results of groundwater contamination survey of RWTSS using the push-drilling sampling system (Waterloo Profiler) which was performed in July — August 2015. The field work was carried out by an international expert team (see affiliations of authors) within the framework of the EC technical assistance project to Ukraine U4.01/10CDF "Support for radioactive waste management in Ukraine".

The groundwater survey of RWTSS pursued the following objectives:

- to characterize radioactive contamination of groundwater in the surveyed sectors of the RWTSS at different distances downstream from the waste burials;
- to assess the temporal dynamics of radioactive contamination of groundwater (compared to previous surveys of 1992-2000, where possible);
- to characterize the hydro-chemical conditions and their influence on the geo-migration of radionuclides.

The survey covered the following sectors located in the areas with the highest levels of contamination by radioactive fallout due to the Chernobyl

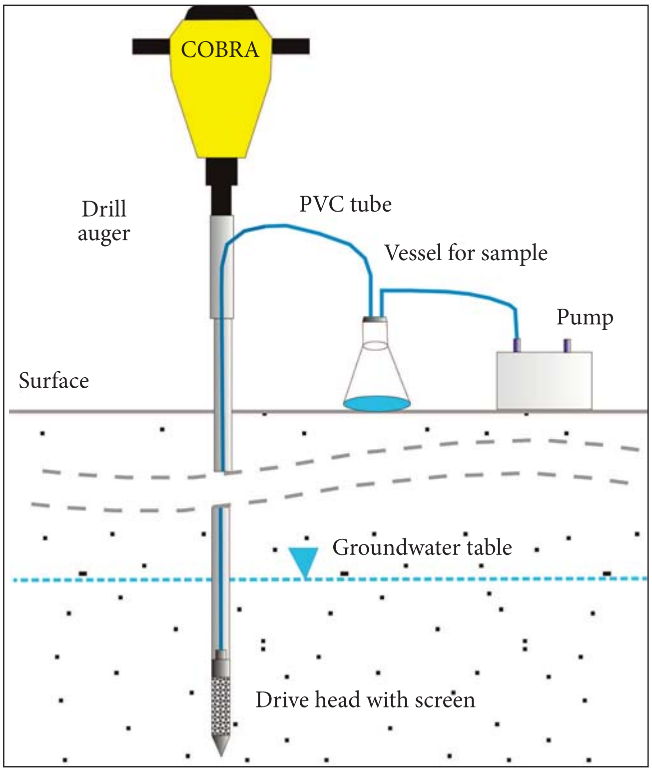

Fig. 1. Groundwater sampling using Waterloo Profiler push-drill auger and Cobra TT percussion hammer. (a) Scheme of application of Waterloo Profiler for groundwater sampling; (b) Drive heads with screen of original design by the Institute of Geological Sciences

accident: "Red Forest", "Staraya Stroybaza", "Yanov Station", and "Neftebaza". The results of groundwater survey were further used in the project U4.01/10CDF to check and calibrate radionuclide transport models used in safety assessments for the RWTSS. The overview of results of safety assessment studies in order to prioritize the remedial measures for the RWTSS is provided in (Molitor et al., 2017).

Methods of field works and analytical studies

Field works

For hand drilling of one-time groundwater sampling boreholes, the Waterloo Profiler drill auger was used with the Cobra TT gasoline-powered percussion hammer (Fig. 1). The contaminated topsoil layer (approximately 20 cm thick) was removed at drilling locations (to preclude contamination of drill hole from the surface). Groundwater sampling was carried out from the depth interval of 0.5–1 m below the groundwater table. Groundwater sampling was conducted using a peristaltic pump.

In the "Red Forest" RWTSS sector the existing small diameter (1–2 inch) shallow wells were used for groundwater sampling, which were installed at this site by various organizations (Institute of Geological Sciences — IGS, Research Institute of Industrial Technologies — NIPIPT) during the period of 1992–2000. These wells usually have 0.5–1 m long screens and allow sampling groundwater from the upper part of the unconfined aquifer immediately below the groundwater table. Wells were purged prior to sampling (by pumping at least 3 well volumes). Coordinates of sampling locations were recorded using GPS. The pH, Eh, conductivity and temperature of collected samples were measured in field conditions using the portable multi-meter WTW Multi 350i.

Analytical measurements

Analytical studies on groundwater samples were carried out in the laboratory of SSE "Ecocenter" in Chernobyl (strontium-90, cesium-137), as well as in the Institute of Geological Sciences (strontium-90). Upon arrival to laboratory the water samples were filtered through the 0.45 μm filter. In the laboratory of the "Ecocenter", the strontium-90 was determined by the radiochemical method. Radiostrontium was separated from the solution by precipitation of carbonates (by the addition of sodium carbonate and sodium hydroxide). The

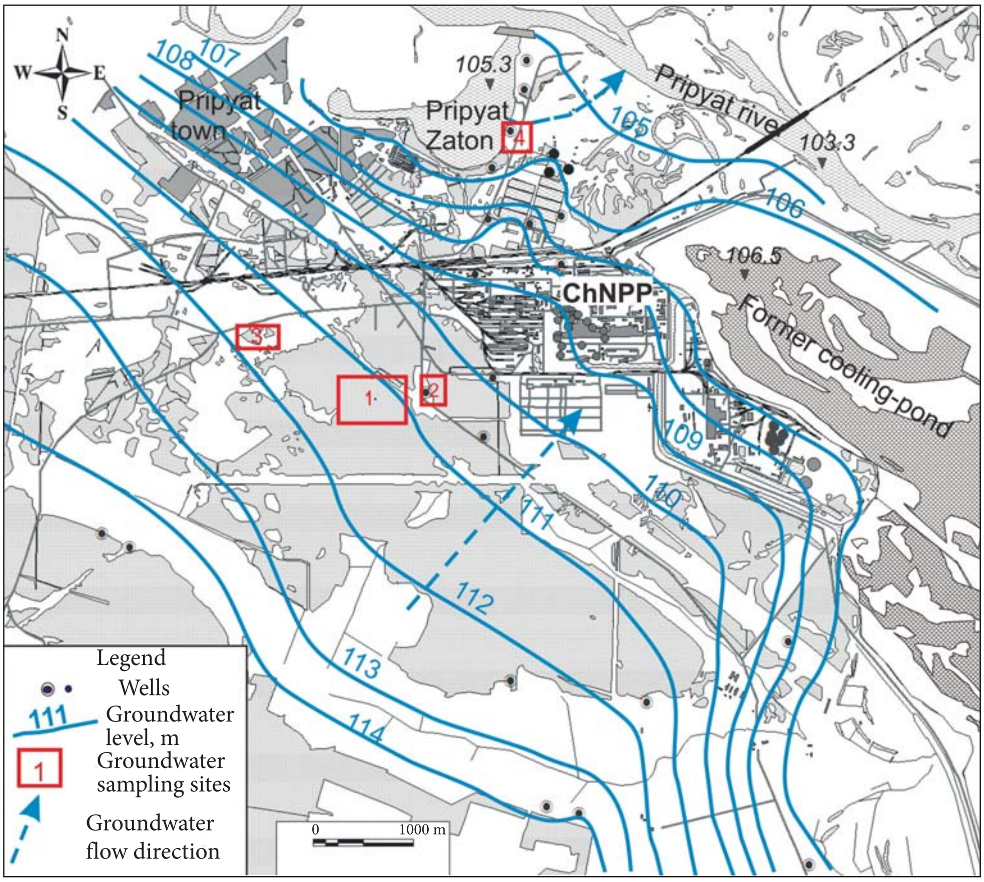

Fig. 2. Scheme of hydraulic head isolines in the unconfined aquifer in Quaternary deposits in the 10-km zone of ChNPP in July 2015 (based on data of IGS, SSE "Ecocenter")

chemical yield of strontium-90 was determined by the weight method by adding a stable strontium label. The activity of strontium-90 in the precipitate was determined by beta-radiometry using NRR-610 (TESLA). Cesium-137 was extracted by filtration of a water sample through an ion-exchange resin ("ANFEG", manufactured by "Ecosorb" LLC, Russia) followed by determination on an ion-exchange material using SEG-002 "AKP-P" gamma-spectrometer equipped with the high purity germanium detector ("Atomprylad", Kyiv). In the laboratory of the IGS, the strontium-90 was determined by direct beta-spectrometry on groundwater samples. Radiometric measurements were carried out using the SEB-01 beta spectrometer ("Atomprylad", Kyiv).

Table 1. **Radiation characteristics of materials stored in surveyed waste burials (mean values of activity concentration as in 2015; based on data of SSE "Central Enterprise on Management of Radioactive Wastes", Chernobyl)**

RWTSS	Waste burial	Cesium-137, Bq/kg (analytical err. 5–10%)	Strontium-90, Bq/kg (analytical err. 10–20%)
"Red Forest"	1-B	3.6E + 05	2.5E + 05
"Red Forest"	4-TB	1.3E + 05	8.6E + 04
"Red Forest"	6-TB	1.6E + 05	1.1E + 05
"Red Forest"	7-TB	4.7E + 05	3.2E + 05
"Red Forest"	10-T	6.7E + 05	4.6E + 05
"Red Forest"	22-T	6.2E + 05	4.26E + 05
"Neftebaza"	201-T	1.4E + 05	9.66E + 04
"Neftebaza"	202-T	1.5E + 05	1.1E + 05
"Neftebaza"	204-T	1.1E + 05	8.1E + 04
"Staraya Stroybaza"	33-B	2.2E + 06	3.3E + 05
"Yanov Station"	26-B	2.5E + 04	1.8E + 04

Results

Radioactive contamination of groundwater in RWTSS sectors

A number of "representative" radioactive waste burial sites was selected for groundwater sampling in the surveyed RWTSS sectors (Table 1). Activity concentration ratio of cesium-137 and strontium-90 in material of waste burials constitute about 1.4 (as in 2015), which corresponds to the composition of the irradiated nuclear fuel of Chernobyl Unit 4 (taking into account the radioactive decay since the time of accident). The exception in the burial no.33-B

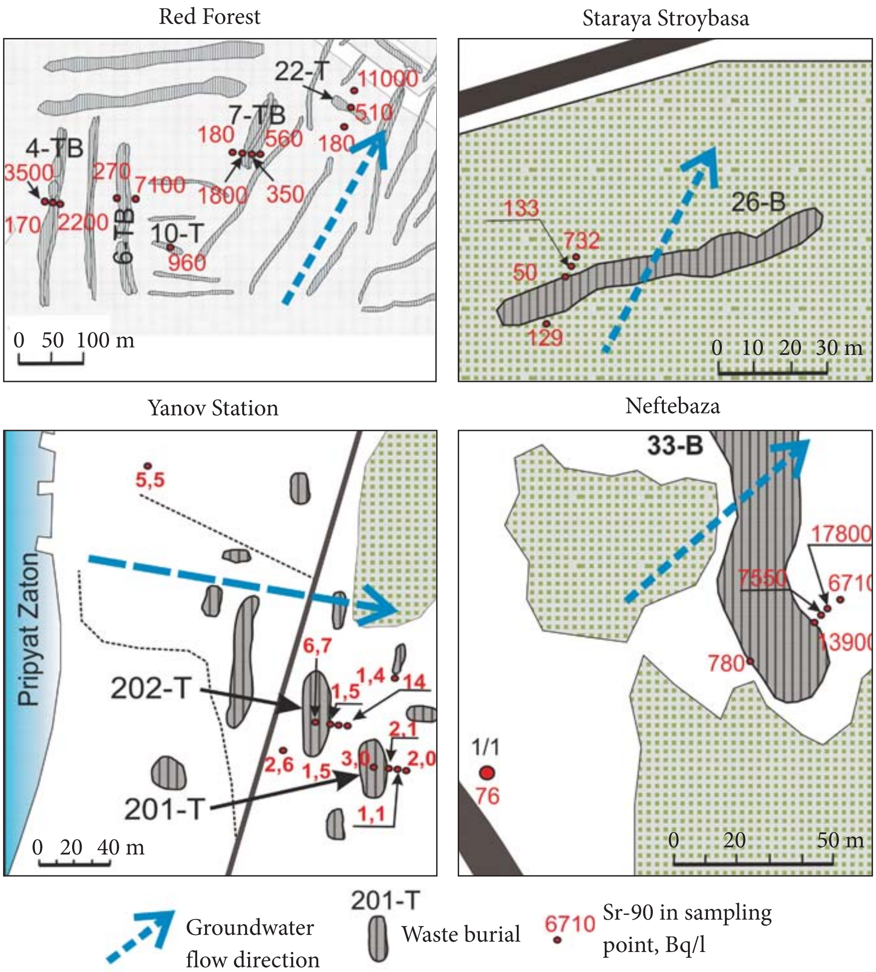

Fig. 3. Concentrations of strontium-90 in groundwater in the RWTSS sectors (July - August 2015). Locations of sampling sites are shown in Fig. 1

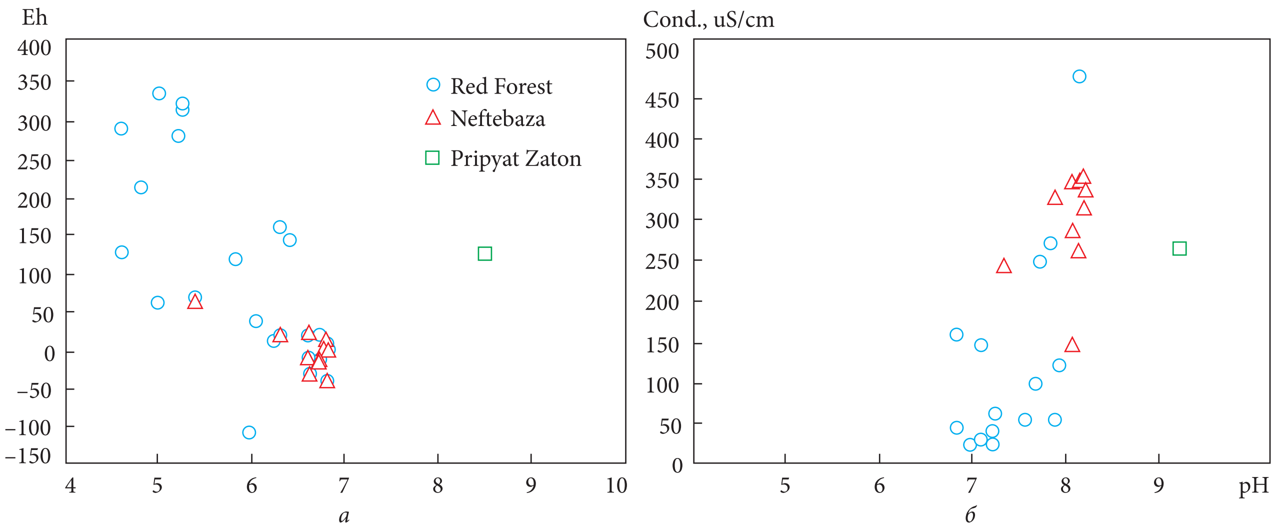

Fig. 4. Diagrams of the hydro-chemical parameters for the RWTSS "Neftebaza", "Red Forest" and Pripyat Zaton (July-August 215)

in the RWTSS "Staraya Stroybaza". This waste burial has an anomalously high cesium-137 to strontium-90 activity concentration ratio of 6.7, which can be explained by presence in waste material of high proportion of condensation component of Chernobyl fallout enriched by cesium-137.

In the "Red Forest" sector, the choice of waste burials for groundwater sampling was dictated by the existence of monitoring wells in the vicinity of these burials. In the "Neftebaza" sector, waste trenches were selected, which were surveyed in the previous years by the State Enterprise "Science — Technical Center on Complex Radioactive Waste Management" (SE "STC KORO", Zhovty Vody). In the RWTSS sectors "Staraya Stroybaza" and "Yanov Station", groundwater sampling at the respective radioactive waste burial sites was carried out for the first time.

Hydrogeological conditions in the near zone of ChNPP at the time of sampling are illustrated in Fig. 2. The groundwater flow in the unconfined aquifer occurs from RWTSS sectors towards the Pripyat River and residual lakes in the area of the former cooling pond of the ChNPP. To the north from ChNPP is situated the Pripyat Zaton reservoir (pond), which represents the dead channel of the Pripyat River separated from the main river

Table 2. **Groundwater contamination at the RWTSS in the 10 km zone of ChNPP in July-August 2015 based on samp**

RWTSS	Longitude	Latitude	Nearest waste burial	Sampling point	Depth to groundwater, m
"Red Forest"	51 23.089	30 04.064	1-B	Well IGN-1B	2.51
" "	51 22.983	30 03.928	4-TB	Well 1	2.81
" "	51 22.982	30 03.932	4-TB	Well 2	4.68
" "	51 22.988	30 03.967	4-TB	Well 4	2.94
" "	51 22.989	30 04.017	6-TB	Well 9	2.32
" "	51 22.989	30 034.035	6-TB	Well 12	2.18
" "	51 23.007	30 04.162	7-TB	Well 14	1.3
" "	51 23.009	30 04.171	7-TB	Well 15	2.33
" "	51 23.009	30 04.190	7-TB	Well 16	2.33
" "	51 23.009	30 04.197	7-TB	Well 17	1.73
" "	51 22.942	30 04.092	10-T	Well 35	2.8
" "	51 23.009	30 04.181	7-TB	Well 7-TB.	2.18
" "	51 23.028	30.04.198	22-T	Well 3-95-2	4.02
" "			22-T	Well 4-02-2	4.45
"Neftebaza"			22-T	Well 5-99	2.95
"	51 24.331	30 05.334	204-T	Well 2-HH	2.94
"	51 24.320	30 05.304	202-T	Well 8-HH	2.89
"	51 24.522	30 05.545	201-T	Auger, 0 m from waste burial	2.6
"	51 24.521	30 05.554	201-T	Auger, 2,5 m from waste burial	2.6
"	51 24.521	30 05.554	201-T	Auger, 5 m from waste burial	2.6
"	51 24.521	30 05.554	201-T	Auger, 10 m from waste burial	2.6
"			202-T	Auger, 0 m from waste burial	2
"			202-T	Auger, 2,5 m from waste burial	2
"	51 24.544	30 05.531	202-T	Auger, 5 m from waste burial	2
"			202-T	Auger, 10 m from waste burial	2
"	51 24. 613	30 05.410		Pripyat Zaton (surface water)	
"Staraya Stroybaza"	51 23.029	30 04.721	B-33	Auger, 0 m from waste burial	4
" "			B-33	Auger, 2,5 m from waste burial	4
" "			B-33	Auger, 5 m from waste burial	4
" "			B-33	Auger, 10 m from waste burial	4
" "			B-33	Auger, 5 m upstream from waste burial	4
"Yanov Station"	51 23.234	30 03.149	B-26	Auger, 0 m from waste burial	1.75
" "			B-26	Auger, 2,5 m from waste burial	1.75
" "			B-26	Auger, 5 m from waste burial	1.75
" "			B-26	Auger, 5 m upstream from waste burial	3

Note: For groundwater samples from "Staraya Stroybaza" and "Yanov Station" strontium-90 was analyzed in the labo carried out in the laboratory of the SSE "Ecocenter", Chernobyl.

channel by a protective dam. The water level in Pripyat Zaton (105.3 m a.s.l.) is 2 m higher than the mean level in Pripyat River (103.3 m a.s.l.). This results in water seepage from Pripat Zaton through its banks towards the river.

The Fig. 2 also shows the layout of groundwater sampling sites in the respective RWTSS sectors. Locations of groundwater sampling points with respect to individual waste burials are shown in

ling using shallow wells and a push-drill auger

pH	Eh, mV	Cond, μS/cm	^{90}Sr, Bq/l	Err., %	^{137}Cs, Bq/l	Err., %
5.2	282	24	1 200	9	0.097	50
4.62	293	158	3 500	9	Not determ.	
4.6	130	44	170	9	” ”	
6.3	160	51	2 200	9	” ”	
4.8	214	23	270	9	” ”	
5	62	145	7 100	9	” ”	
5.96	−105	97	660	9	” ”	
5.81	121	53	1 800	9	” ”	
6.03	40	250	350	9	” ”	
6.4	145	118	560	9	” ”	
6.23	12.8	270	960	9	” ”	
6.74	21	476	790	9	” ”	
5.25	315	39	510	9	0.08	49
5.27	327	58	11 000	9	0.220	30
5.01	338	30	180	9	0.210	30
6.6	22	147	1.4	10	0.600	15
6.8	−39	315	2.6	10	0.090	49
6.3	20	328	3.0	10	0.088	49
6.6	−7.7	288	2.1	9	0.082	49
6.71	−11	264	2.0	9	0.170	34
5.4	66	244	1.1	9	0.091	49
6.81	1.6	338	6.7	9	0.089	49
6.71	−14.6	348	1.5	10	0.062	55
6.8	10	354	1.5	10	0.061	58
6.61	−30.5	348	14	10	0.069	60
8.5	127	263	11	10	2.100	11
4.47	152.4	191	13 900	24.8	0.08	42
4.5	155.4	220	7 550	14.3	0.06	48
8.05	−60.9	255	17 800	12.5	0.08	41
5	118	267	6 710	12.5	0.06	45
5.6	85.4	43	780	16.2	<0,04	
4.13	170	76	50	52	<0,04	
4.7	150	58	133	36.5	<0,04	
4.9	120	123	732	24.8	<0,04	
5.2	101	122	129	18.4	<0,04	

ratory of the IGS; all other analytical determinations were

Fig. 3 (a)–(d). The expected directions of groundwater flow in the vicinity of burials are shown by arrows. These flow directions were determined based on measurements of groundwater levels in wells (see Fig. 2). Sampling was performed along monitoring well profiles (or from temporary drilling points) located in the immediate vicinity of the waste burials at distances ranging from several meters to 10 m in downstream direction. In addition, groundwater samples from upstream locations were collected.

Determining the concentration of strontium-90 in groundwater was of main interest, as this radionuclide poses major risks of groundwater and surface water contamination in the Chernobyl exclusion zone (Bugai et al., 1996; Kireev et al., 2013, 2019). The concentration of cesium-137 in groundwater was also measured. The results of the groundwater contamination survey of the RWTSS sectors are summarized in Table 2 and illustrated in Fig. 3.

The higher specific activities in groundwater of the RWTSS sectors are observed for strontium-90. At RWTSS "Red Forest" the strontium-90 concentrations varied from 180 to 11000 Bq/l; at "Staraya Stroybaza" — from 780 to 17800 Bq/l; at "Yanov Station" — from 50 to 732 Bq/l, at "Neftebaza" — from 1.1 to 14 Bq/l. For comparison, the maximum permissible activity concentration of strontium-90 in drinking water according to the DR-2006 regulations (Ministry of Health of Ukraine, 2006) is 2 Bq/l. The highest levels of groundwater contamination by strontium-90 are observed for waste burials that contain waste with maximum specific activity (in the "Staraya Stroybaza" and "Red Forest" RWTSS, see Table 1). At the RWTSS "Starya Stroybaza" elevated strontium-90 concentrations in groundwater were sampled at up to 10 m distance downstream from the waste burial (clamp B-33). Somewhat lower levels of groundwater contamination with strontium-90 and cesium-137 for the 'Yanov Station" compared to "Red Forest" and "Staraya Stroybaza" may be due to relatively low specific activity of waste in this RWTSS compared to other surveyed sectors (see Table 1).

Noticeably lower levels of strontium-90 in groundwater at "Neftebaza" compared to the "Red Forest" are likely to be related to the geological conditions of this site which is the presence of layers of loamy soils with elevated sorption properties underlying the radioactive waste burials at "Neftebaza". The migration of radionuclides from the waste burials at "Neftebaza" has been also likely affected by the specific hydrogeological and hydrochemical conditions of this RWTSS due to the infiltration of water from the Pripyat Zaton into the aquifer. The geochemical conditions in groundwater below the RWTSS are discussed in more detail below in paragraph 3.2.

The concentrations of cesium-137 in groundwater at the surveyed RWTSS sectors are significantly lower compared to strontium-90, and vary from values below the detection limit (<0.04 Bq/l) to 0.6 Bq/l, while most values are of an order of 0.1 to 0.2 Bq/l or less. For comparison, the maximum permissible activity concentration of cesium-137 in drinking water according to the DR-2006 regulations is 2 Bq/l (Ministry of Health of Ukraine, 2006). The low mobility of cesium-137 in groundwater is caused by the significant sorption of this radionuclide by the matrix of geological deposits and the fixation (non-exchangeable sorption) by clay minerals (Cornell, 1993; Bugai et al., 2020).

Levels of radioactive contamination of groundwater of RWTSS by strontium-90 and cesium-137 measured during the survey in 2015 are generally comparable to the levels of contamination of the respective sectors based on sampling surveys in 1992-1998 (Table 3). Thus, during the last two decades the conditions for radioactive contamination of groundwater were observed at RWTSS, which are relatively stable over this time span. This may be due to the gradual dissolution of the fuel particles in the waste burials and the subsequent release of mobile forms of radionuclides to groundwater, so that vertical inflow of radionuclides from waste burials compensate for horizontal transport in the aquifer by advection-dispersion process and radioactive decay. In particular, it was established by (Kashparov et al., 2019) that by 2015 about half of the strontium-90 activity in trench no.22-T in the "Red Forest" RWTSS still remained associated with that of the non-dissolved fuel particles (from this last fraction about ~30% of activity was associated with the very stable zirconium-matrix fuel particles).

The exception from the general picture is the RWTSS "Neftebaza", where markedly lower levels of groundwater contamination with strontium-90 were observed in 2015 compared to data from 1998. The possible reasons for this are discussed in the next paragraph.

It should be noted, that the strontium-90 concentrations in groundwater sampled in the reported survey are much higher than concentrations that are observed during last decade in the monitoring wells of the SSE "Ecocenter" (Kireev et al., 2013, 2019). For example, ^{90}Sr concentrations in wells no.1/1, 2/1 and 2/2 of SSE "Ecocenter" situated at RWTSS "Staya stroybaza" in 2015 ranged from 22 to 76 Bq/l, while ^{90}Sr concentrations in groundwater based on push drill sampling reached 17600 Bq/l (see Table 2).

Hydro-chemical conditions

In the course of groundwater sampling, measurements were also made in the field of pH, Eh and conductivity. The Eh parameter determines the redox conditions in groundwater: the positive values correspond to the oxidizing conditions, while the

Table 3. **Data of studies on radioactive contamination of groundwater in RWTSS carried out by various organizations, in 1992-1998 (Antropov et al., 2001)**

RWTSS	Waste burial	Year of survey	Organization that conducted survey	Maximum radionuclide activity concentration, Bq/l		
				^{90}Sr	^{137}Cs	$^{239+240}$Pu
"Red Forest"	19-T	1992	NIPIPT	3600	No data	0.42
" "	20-T	1992	"	30000	" "	0.33
" "	29-T	1992	"	14000	" "	0.15
" "	22-T	1998	IGS	16000	0.3	0.18
" "	4-BT*	1998	"	2700	350*	5.0
"Yanov Station"	14-T	1995	STC KORO	3990	No data	No data
"Neftebaza"	4-T	1998	" "	613	0.4	0.039
"	201-T	1998	" "	274	0.3	<0.001

Notes: * High ^{137}Cs value for waste burial 4-BT can be explained by the fact that the waste burial was flooded by groundwater, and sample was taken directly from the water-saturated waste material.

negative values to reducing hydro-chemical conditions. The conductivity parameter depends on the total dissolved solids (TDS, content of the major ions): higher conductivity indicates a higher TDS value of the sample. The results of the corresponding measurements are shown in Table 2 and in Fig. 4.

It can be seen that the results of hydro-chemical measurements for the "Neftebaza" are essentially different compared to other RWTSS ("Red Forest", "Yanov Station", "Staraya Stroybaza"), which can be explained by the different groundwater recharge mechanism to the unconfined aquifer.

For the RWTSS "Red Forest", "Yanov Station", "Staraya Stroybaza" groundwater recharge is formed by atmospheric precipitation. Such groundwater is characterized mainly by oxidizing conditions (positive Eh), relatively low pH (about 5) and low TDS (and respectively low conductivity). Downstream of the trenches, the TDS of the waters may increase slightly, and Eh may change towards reducing conditions due to the leaching of ions from the waste material and the bio-degradation of organic materials in the waste burials (Bugai et al., 2012b).

A different picture is observed for the RWTSS "Neftebaza". Here, the groundwater is characterized by a relatively high conductivity (close to the value for the water of the Pripyat Zaton), reducing conditions (negative Eh) and pH values shifted towards alkaline conditions. In our opinion, this is due to the infiltration and seepage in the aquifer of the surface waters of the Pripyat Zaton towards the Pripyat River. The water level in the Pripyat Zaton, which is isolated from the river by a protective dam, is about 105.3 m a.s.l., and in the Pripyat River — about 103.3 m a.s.l. (in low flow conditions), which results in a hydraulic head gradient, and creates condition for seepage from the Pripyat Zaton towards the river. Reducing conditions in groundwater infiltrating to the aquifer from the Pripyat Zaton can be caused by leaching the surface water through the organic-rich bottom sediments in the Pripyat Zaton.

Relatively high discharge rates of the lateral seepage flow from the Pripyat Zaton in the aquifer in the zone of waste burials of the "Neftebaza" could have caused leaching of mobile radionuclide chemical forms (in particular strontium-90), and a decrease in strontium concentrations as in 2015 (see Table 2) compared to the previous survey in 1998 (see Table 3). The concentration of strontium-90 can also be affected by alkaline hydrochemical conditions, which may cause the removal of radiostrontium from the solution in the form of carbonates (Panasyk et al., 2019).

Conclusions

The survey of radioactive contamination of groundwater at waste dump sites (RWTSS) in the 10-km zone of ChNPP carried out in 2015 has shown that the main hazard, as in previous years, is related to groundwater contamination by strontium-90. The strontium-90 concentrations have varied at "Red Forest" from 180 to 11000 Bq/l; at "Staraya Stroybaza" from 780 to 17800 Bq/l; at "Yanov Station" from 50 to 732 Bq/l; at "Neftebaza" from 1.1 to 14 Bq/l.

The concentrations of cesium-137 in groundwater are significantly lower compared to strontium-90 and vary from values below the detection limit (<0.04 Bq/l) to 0.6 Bq/l; while the most values are in an order of 0.1-0.2 Bq/l or less.

The levels of radioactive contamination of groundwater at RWTSS with strontium-90 and cesium-137 measured during the survey in 2015 are in general comparable to the levels of contamination of the respective sectors based to the studies performed in 1992-1998. Thus, at present the conditions of radioactive contamination of groundwater are observed, which are relatively stable over the last 2 decades. This may be due to the gradual dissolution of fuel particles in waste, and, respectively in the gradual leaching of newly released mobile radioactive contaminants into groundwater which compensate for horizontal transport in the aquifer and radioactive decay.

Relatively low levels of groundwater contamination by strontium-90 have been observed for the waste dumps at "Neftebaza" site. Based on the analysis of hydrodynamic and hydro-chemical conditions, it can be assumed that here radionuclide migration conditions are affected by surface water infiltration from the Pripyat Zaton in the direction of the Pripyat River. High discharge rate of seepage from the Pripyat Zaton creates a "wash-out regime" in the aquifer, and clayey soils and alkaline geochemical conditions may favor lowering radiostrontium concentrations in groundwater below waste burials.

It should be noted that the sampling data of radioactive contamination of groundwater in the immediate vicinity of waste burials with the help of the push-drill auger provide significantly higher levels of groundwater contamination in comparison to the data of the regime monitoring network of the SSE "Ecocenter". This confirms that the existing system of hydrogeological monitoring of the RWTSS, which is used by the SSE "Ecocenter", suffers from a number of shortcomings (such as improper locations and design of the observation wells), and it requires further improvement and development.

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РАДІОАКТИВНЕ ЗАБРУДНЕННЯ ПІДЗЕМНИХ ВОД В ПУНКТАХ ЛОКАЛІЗАЦІЇ РАВ В ЧОРНОБИЛЬСЬКІЙ ЗОНІ ВІДЧУЖЕННЯ

Представлені результати обстеження забруднення підземних вод в пунктах локалізації радіоактивних відходів (РАВ) в 10-кілометровій зоні Чорнобильської АЕС, що містять відходи від післяаварійної дезактивації місцевості (зокрема, "рудий ліс", загиблий від екстремальних рівнів радіації в 1986 р.). Відбір проб підземних вод у безпосередній близькості від поховань відходів із застосуванням системи ударного буріння Waterloo Profiler, проведений у липні—серпні 2015 р., показав, що основна небезпека пов'язана із забрудненням підземних вод стронцієм-90. Концентрація стронцію-90 у ґрунтовій воді коливалась для різних поховань відходів від 1,1 до 17 800 Бк/л, що значно перевищує норматив для питної води 2 Бк/л. Концентрація цезію-137 у підземних водах варіювалась від значень нижче межі виявлення (<0,04 Бк/л) до 0,6 Бк/л (тобто менше питного нормативу 2 Бк/л). Результати відбору проб показали, що рівні радіоактивного забруднення підземних вод стронцієм-90 в зоні поховань є відносно стабільними протягом останніх двох десятиліть, що відповідає гіпотезі про поступове розчинення паливних частинок у матеріалах РАВ та подальшій міграції радіоактивних забруднень в підземних водах. Більш низькі рівні стронцію-90 в підземних водах поблизу поховань відходів спостерігалися в пункті локалізації РАВ «Нафтобаза» поблизу Прип'ятського Затону, що, ймовірно, обумовлено специфічними гідрогеологічними та геохімічними умовами цієї ділянки (глинисті ґрунти; підвищені швидкості латеральної фільтрації; відновлювальні лужні геохімічні умови). Отримані дані щодо радіоактивного забруднення ґрунтових вод у безпосередній близькості від поховань РАВ із застосуванням системи ударного буріння показали значно більш високий рівень забруднення ґрунтових вод порівняно з даними режимної мережі моніторингу Державного спеціалізованого підприємства "Екоцентр", яке відповідає за радіаційний моніторинг у Чорнобильській зоні відчуження. Це підтверджує, що існуюча система гідрогеологічного моніторингу пунктів локалізації радіоактивних відходів в 10-км зоні ЧАЕС потребує подальшого вдосконалення та розвитку.

Ключові слова: *аварія на ЧАЕС; стронцій-90; цезій-137; підземні води; моніторинг.*

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РАДИОАКТИВНОЕ ЗАГРЯЗНЕНИЕ ПОДЗЕМНЫХ ВОД В ПУНКТАХ ЛОКАЛИЗАЦИИ РАО В ЧЕРНОБЫЛЬСКОЙ ЗОНЕ ОТЧУЖДЕНИЯ

Представлены результаты обследования загрязнения подземных вод в пунктах локализации радиоактивных отходов (РАО) в 10-километровой зоне Чернобыльской АЭС, содержащих отходы послеаварийной дезактивации местности (в частности, «рыжий лес», погибший от экстремальных уровней радиации в 1986 г.). Отбор проб подземных вод в непосредственной близости от захоронений отходов с применением системы ударного бурения Waterloo Profiler, проведенный в июле—августе 2015 г., показал, что основная опасность связана с загрязнением подземных вод стронцием-90. Концентрация стронция-90 в грунтовой воде колебалась для различных захоронений отходов от 1,1 до 17 800 Бк/л, что значительно превышает норматив для питьевой воды 2 Бк/л. Концентрация цезия-137 в подземных водах варьировалась от значений ниже предела обнаружения (<0,04 Бк/л) до 0,6 Бк/л (т.е. меньше питьевого норматива 2 Бк/л). Результаты отбора проб показали, что уровни радиоактивного загрязнения подземных вод стронцием-90 в зоне захоронений относительно стабильны в течение последних двух десятилетий, что соответствует гипотезе о постепенном растворении топливных частиц в материалах РАО и дальнейшей миграции радиоактивных загрязнений в подземных водах. Более низкие уровни стронция-90 в подземных водах вблизи захоронений отходов наблюдались в пункте локализации РАО «Нефтебаза» вблизи Припятского Затона, что, вероятно, обусловлено специфическими гидрогеологическими и геохимическими условиями этого участка (глинистые грунты; повышенные скорости латеральной фильтрации; восстановительные щелочные геохимические условия). Полученные данные по радиоактивному загрязнению грунтовых вод в непосредственной близости от захоронений РАО с применением системы ударного бурения показали значительно более высокий уровень загрязнения грунтовых вод по сравнению с данными режимной сети мониторинга Государственного специализированного предприятия “Экоцентр”, которое отвечает за радиационный мониторинг в Чернобыльской зоне отчуждения. Это подтверждает, что существующая система гидрогеологического мониторинга пунктов локализации радиоактивных отходов в 10-км зоне ЧАЭС требует дальнейшего совершенствования и развития.

Ключевые слова: *авария на ЧАЭС; стронций-90; цезий-137; подземные воды; мониторинг.*