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MONITORING OF RW STORAGE FACILITY BUILT AS A RESULT OF EI-2 URANIUM-GRAPHITE REACTOR DECOMMISSIONING

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In 2015, the "in situ entombment" (ENTOMB) option was implemented to decommission PUGR EI-2. These activities performed under the Federal Target Program "Nuclear and Radiation Safety in 2008 – 2015" took place at site № 2 of the Pilot Demonstration Centre for Uranium Graphite Reactor Decommissioning (PDC UGR). As the result EI-2, Radioactive Waste Storage Facility (EI-2 RW SF) was constructed.

EI-2, production uranium-graphite nuclear reactor located at PDC UGR site was commissioned in 1958 and shut down on December 28, 1990 after 33 years of operation. EI-2 RW SF was fitted with a system of engineered safety barriers. Experiments and calculations have demonstrated that the system of natural (host rock) and engineered barriers can ensure reliable containment of radionuclides inside the EI-2 storage facility. Moreover, forecasts show that radioactive impact on the public and the environment will be significantly lower than the existing regulatory limits.

EI-2 PUGR decommissioning was a pilot project. Therefore, EI-2 RW SF impact on the public and the environment should be evaluated to demonstrate the safety of the chosen decommissioning method. Thus, a number of EI-2 RW SF key parameters is being monitored and relevant efforts are being implemented to improve the monitoring system.

Keywords: *decommissioning, production uranium-graphite reactor, monitoring, safety barriers, barrier material, RW storage facility.*

Introduction

In keeping with provisions of Production Uranium-Graphite Reactors (PUGR) Decommissioning Concept Suggesting the Implementation of the ENTOMB Option approved by the State Corporation Rosatom, such decommissioning should enable reliable isolation of RW at facility's site ensuring radiation safety of personnel, public and the environment [1]. Practical efforts under this concept involve construction of additional safety barriers ensuring reliable isolation of radionuclides contained in reactor materials and structures including all non-dismantlable and non-removable structure elements of reactor units (graphite stack, supporting steel structures, biological shield). Thus, barrier properties inherent to natural geological structures (host and overlying rocks) and those of the constructed engineered barriers, as well as physical and mechanical properties of RW containing materials act together to ensure the long-term safety of the established radioactive waste storage facility (RW SF).

PUGR EI-2 decommissioning designs

Shutdown uranium-graphite reactor EI-2 of the Pilot Demonstration Centre for Uranium-Graphite Reactor Decommissioning was chosen to implement the pilot decommissioning project following

The translation is done by N. S. Cebakovskaya

Figure 1. PUGR EI-2: before decommissioning in 2011 (left), after completed decommissioning in 2015 (right)

the ENTOMB option. Significant amounts of radionuclides, including the long-lived ones (^{14}C, ^{36}Cl, actinides) have been accumulated in reactor structures during its operational life.

An integrated approach based on the points mentioned below was followed to demonstrate scientific and technical feasibility of PUGR EI-2 (Figure 1) decommissioning. This approach ensures that:

- Intervention levels (IL) specifying the maximum contents of isolated radionuclides in the environmental media shall not be exceeded;
- Parameter values set in relevant regulations and specifying the radiation impacts associated with the isolated radionuclides shall not be exceeded.

From the engineering perspective, practical efforts enabling the implementation of this decommissioning method can be summed up as follows [2]:

- Complete dismantlement and removal of dismantled systems and equipment from the reactor building;
- Removal of RW accumulated in the reactor building except for permanent PUGR structure elements (graphite stack, supporting steel structures, biological shield);
- Concrete reinforcement of sub-reactor spaces;
- Construction of engineered barriers by void-free filling of free spaces inside the graphite stack, reactor pit and reactor premises by barrier materials [3—6];
- Dismantlement of surface structures and construction of engineered barriers (protection screen) above the RW SF (Figure 2).

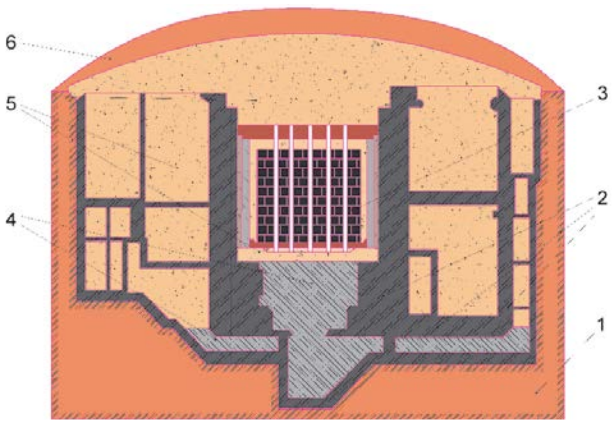

Figure 2. RW storage facility EI-2 at PDC UGR site:
1 – host rocks, 2 – walls of reactor pit and structures (concrete);
3 – graphite stack and main metal structures of the reactor;
4 – cased voids underneath the reactor; 5 – clay-based barrier material inside the reactor voids and premises surrounding the reactor pit; 6 – protection shield

During the feasibility study, purpose-developed software was used to estimate radionuclide release from RW SF EI-2, to forecast their migration into the environment and relevant fluctuations in the parameters associated with the radiation impact on the population [7]. Input data used in these calculations were obtained during engineering and radiation survey of the reactor, laboratory and prototype tests of barrier material and host rock properties, as well as geophysical and geochemical investigations performed at the reactor site.

Implementing PUGR EI-2 decommissioning

PUGR EI-2 decommissioning project involved complete dismantlement of auxiliary equipment, structures, pipelines, process lines. In parallel, RW accumulated during reactor operation in process vaults and SNF pools were collected and removed from the building. The dismantled equipment and removed RW were processed and conditioned. Sub-reactor space, EI-2 reactor basement up to lower steel structures, auxiliary premises at the lower levels were grouted. Engineered barriers were installed inside the reactor pit. Their construction involved the use of void-fee grouting technology enabling to fill up the voids with clayey-based materials [5, 6]. The first stage involved grouting of sub-reactor supporting metal structures and side

Figure 3. Construction of additional safety barriers inside PUGR EI-2 pit: the main hall during the backfilling process (left), barrier material inside the void spaces of the reactor pit (center), inspection channel inside the technological shaft (right)

spaces between the reactor shell and side biological protection tanks (Figure 3). Further on, backfilled were the process cells of the graphite stack. At the final stage, void spaces inside the structures located above the reactor and auxiliary premises were backfilled including transport and process tanks. The amount of clayey mixtures used in the engineered barrier construction at EI-2 site totaled some 40,000 m^3.

Decontamination of engineered structures was followed by the dismantlement of reactor building surface structures. Special equipment and devices were used to minimize dust generation during the dismantlement process. A multilayer protection screen (Figure 4) filled up with barrier material was installed above the reactor pit at the site of the demolished reactor building.

Inspection channels were fitted inside RW SF EI-2 to monitor the state of its engineered barrier structures (Figure 5, 6):

- In the middle of the reactor — channel № 1;
- On the periphery of the building (inside the technological shaft ShT-2) — channel № 2;
- On the periphery of the reactor pit (inside the reactor “space”) — channel № 3.

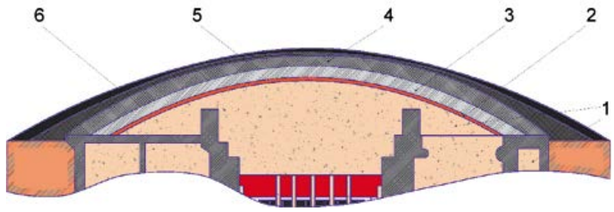

Figure 4. Layout of the protection screen at RW SF EI-2 (PDC UGR): 1 – clay-containing backfill material; 2 – medium-grained sand; 3 – plastic clay; 4 – gravel; 5 – medium-grained sand; 6 – vegetation layer

In keeping with NP-091-14 provisions [8], in June 2016 final engineering and radiation survey of the RW storage facility established as the result of EI-2 decommissioning project was performed. The survey involved the following activities:

- Mapping the distribution of radiation characteristics for alpha-, beta- and gamma radiation at the surface of the protection screen and the adjacent territories;
- Sampling the soils collected from the protection screen and RW SF EI-2 adjacent territories followed by gamma spectrometric analysis and identification of the samples’ specific activity;

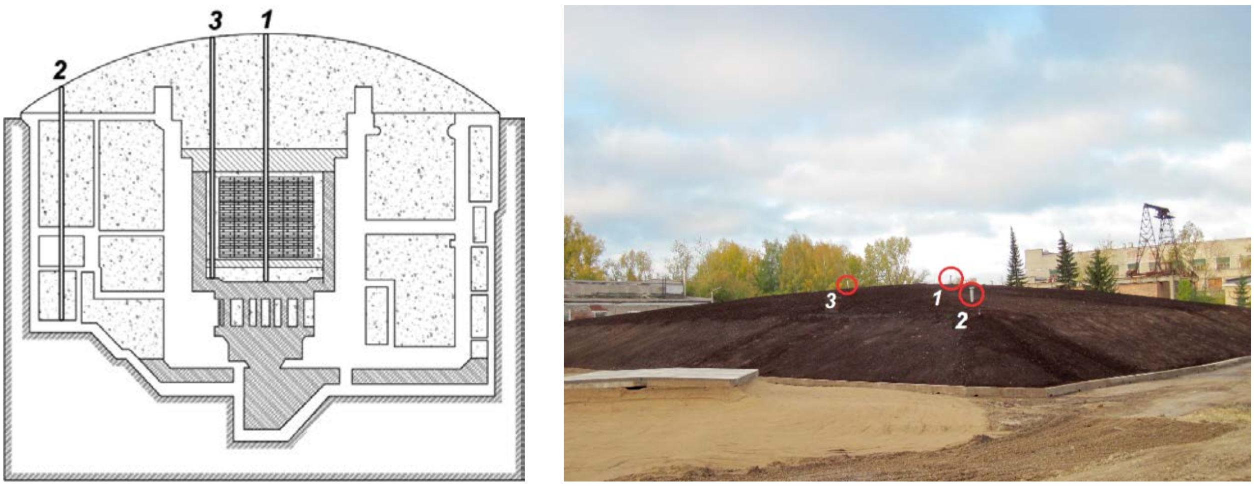

Figure 5. Inspection channel system inside RW SF EI-2

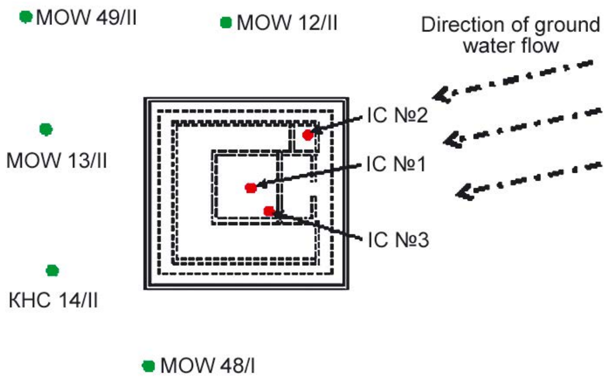

Figure 6. Layout of ● nspection channels (IC) inside RW SF EI-2; ● monitoring and observation wells (MOW) within the boundaries of RW SF EI-2 impact zone

- Evaluating the state of inspection channels by means of remote visual inspection;
- Evaluating the state of the protective screen and the adjacent territories by means of visual inspection, GPR and electrical exploration.

The survey has demonstrated that the as-built facility corresponds to the design provisions.

Monitoring at RW SF EI-2 site

In keeping with NP-055-2014 provisions [8], safety of RW SF is ensured by a safety barrier system (engineered and natural barriers) constructed to prevent radionuclide release into the environment. The long-term safety of the isolated RW should not be compromised in case if one of the barriers loses its sealing capacity or an external event of natural or man-made origin occurs (multibarrier principle).

Considering that PUGR EI-2 decommissioning was a pilot project, demonstrating the safety of the implemented design solutions is believed to be a key task for the established RW SF. An integrated monitoring system enabling to assess the state of RW SF barrier system and its impact on environmental media is required to be implemented ensuring systematic control over a number of key parameters.

These RW SF EI-2 parameters are currently being monitored in keeping with relevant provisions of TR-170000-002-2015 Technical Guidelines for Non-Retrievable RW Facility and RB-R-080000-002-2015 Radiation Monitoring Regulation for Radioactive Waste Storage Facilities:

- Monitoring the ground water using a network of 33 stationary monitoring and observation wells (MOW) at site № 2, including 5 MOWs located inside the boundaries of the proposed RW SF EI-2 impact zone (Figure 6);
- Radiation survey of RW SF EI-2 area and soils;
- Temperature monitoring inside the graphite stack.

Key monitoring findings

The following measurements and investigations were performed to monitor the ground water using a network of monitoring and observation wells (MOW) located inside RW SF EI-2 impact zone:

- Ground water level measurements inside observation wells;
- Formation water sampling;
- Geophysical investigations by observation wells gamma logging;
- Identifying the characteristics of ground water micro components (pH, total hardness, NH_4^+, Fe (tot), NO_3^{2-}, Cl^-, SO_4^{2});
- Identifying the total α-, β- activity, specific activity of ^{90}Sr and γ- emitting radionuclides.

Relevant values of controlled criteria, as well as lower detection limits according to chemical contents and specific activity of radionuclides contained in ground water samples are provided in Table 1.

Table 1. Parameters identified for ground water samples

Identified parameters	Units	Controlled criteria values	Lower detection limit
pH		7–9*	1.0
Total hardness	mg-eq/dm^3	7.0*	0.6
NH_4^+	mg/dm^3	2.0* (nitrogen content)	0.5
Fe (total)	mg/dm^3	0.3*	0.02
NO_3^{2-}	mg/dm^3	45.0*	0.1
Cl^-	mg/dm^3	350.0*	0.5
SO_4^{2-}	mg/dm^3	500.0*	0.5
Σβ-activity	Bq/dm^3	1.0**	0.01
Σα-activity	Bq/dm^3	0.2**	0.01
^{60}Co	Bq/kg	40.0**	0.1
^{90}Sr	Bq/kg	4.9**	0.2
^{134}Cs	Bq/kg	11.0**	0.1
^{137}Cs	Bq/kg	11.0**	0.1

Note: * — MPC (maximum permissible concentration),
** — IL (intervention level)

In 2016—2017, ground water monitoring results for the RW SF EI-2 impact zone were as follows:

1. Ground water level measured in MOW located inside the proposed RW SF EI-2 impact zone (MOW № 12/I, 49/II, 13/II, 48/I, 14/II) is considered to be stable and remains within possible seasonal fluctuation limits accounting for 96—103 m relative to the level of the Baltic Sea which corresponds

to some ~22—29 m relative to ground surface level in RW SF vicinity. Dynamics of ground water level fluctuations measured in MOWs located inside the proposed RW SF EI-2 impact zone is shown in Figure 7.

2. Gamma radiation dose rate (DR) measurements performed for the dry part of boreholes using gamma logging with a discreteness of 1 m did not reveal any abnormal leaps or positive dynamics providing for DR growth (within the measurement error) at RW SF EI-2 post-construction stage (Figure 8).

3. Chemical analysis and radionuclide content estimations in 2016—2017 showed that:

- Maximum permissible concentrations specified for the main macro components are not exceeded inside the proposed RW SF EI-2 impact zone (MOWs № 12/I, 49/II, 13/II, 48/I, 14/II);
- Microchemical contents of the ground water is quite similar to the background values;
- Σβ- and Σα- activity of water samples collected from the abovementioned wells is lower than the background levels specified for RW SF EI-2 region;
- Specific activity of identified man-made radionuclides (see Table 1) contained in the water samples collected from the abovementioned wells is lower than relevant detection limits;
- In 2016—2017, no abnormal leaps in the dynamics of the indicators used to evaluate the state of ground water inside RW SF EI-2 impact zone were identified.

Acquiring latest information on radiation characteristics of the protection screen surface layer and the adjacent territories, is seen as the key task specified for radiation survey activities covering the territory and soils in RW SF EI-2 region. Such radiation surveys involve:

- Mapping the distribution of alpha-, beta- and gamma radiation characteristics for the surface of the protection screen and the adjacent territories;
- Soil sampling from the protection screen and RW SF adjacent territories;
- γ- spectrometric analysis of soil samples.

Radiation survey results can be summed up as follows:

- The lowest detection limits are not exceeded for α- and β- radiation fluxes above the structure itself (protection screen surface) and the rest of adjacent territories accounting for < 0.1 particle/cm^2·min and < 5 particle/cm^2·min correspondingly;
- γ-radiation dose rate above the structure itself (protection screen surface) and the rest of adjacent territories is lower than 0.2 μSv/hour;
- spectrometric analysis of near-surface soil samples has shown that relevant contents of ^{137}Cs is very low accounting for 3—5 Bq/kg (lower that minimum significant specific activity) being lower than the average contamination level for PDC UGR site № 2.

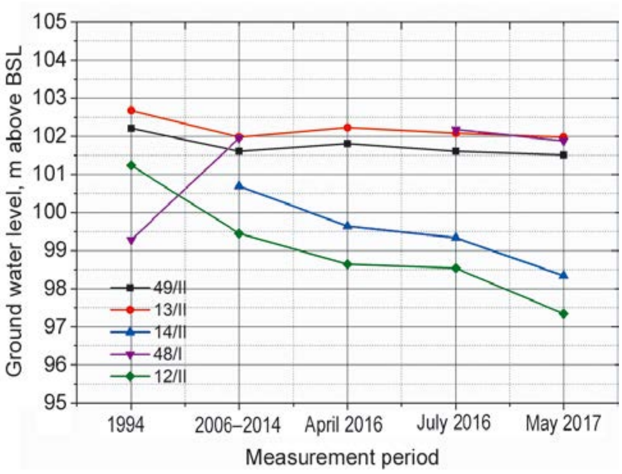

Figure 7. Fluctuations in the ground water levels measured in MOWs located inside the proposed impact zone of EI-2 RW SF (BSL — Baltic Sea level)

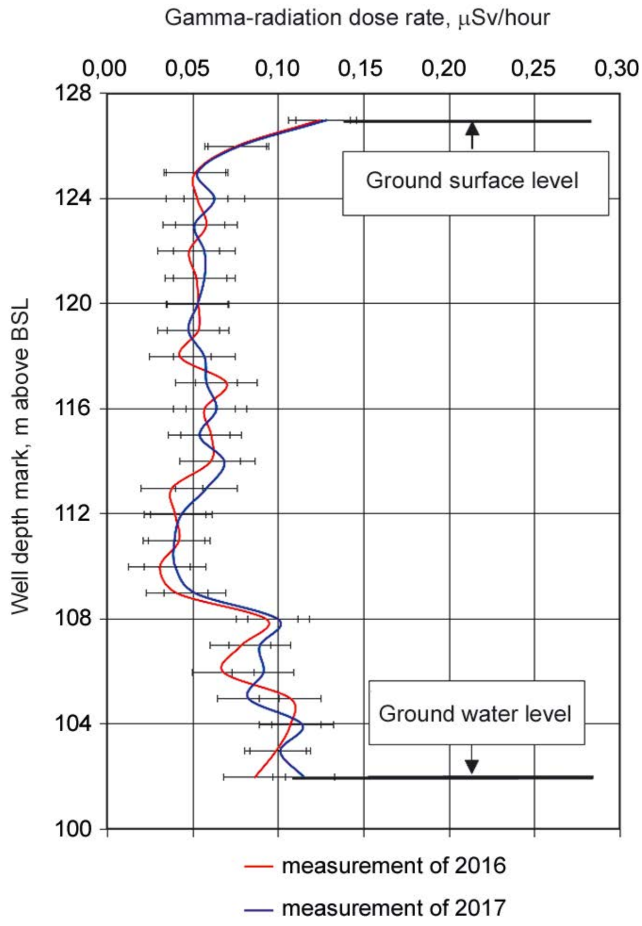

Figure 8. Gamma scanning curve in the borehole MOW № 12/II in RW SF EI-2 impact zone (BSL — Baltic Sea level)

Graphite stack temperature monitoring has shown that its temperature remains stable notwithstanding the season accounting for + (12 ± 1) °C.

Prospects for RW SF EI-2 monitoring system enhancement

Long-term safety of the constructed RW storage facility can be ensure only if relevant properties and parameters of natural and engineered barriers defining the robustness of the isolation system are maintained. Barrier system stability can be ensured by means of monitoring aiming to control the state of engineered barriers and the radiation and ecological state of the natural barrier.

To address this issue under the State Contract of February 20, 2015 № N.4d.21.2.1.15.1003, methods and equipment (Figure 9) enabling to monitor a number of engineered barrier parameters via inspection channels fitted within RW SF EI-2 were developed and tested in 2015. This system also involved the use of neutron-neutron and neutron-gamma ray logging (Table 2).

Presence of radioactive materials inside the facility was also accounted for in the decision-making process on most effective monitoring methods and logging complex layout [10].

Water content inside the barrier material was measured using neutron-gamma logging complex via inspection channel IC №2 located inside the technological shaft ShT-2. It was demonstrated that the water content around the inspection channel is lower than 4% by mass (Table 3).

The device used for neutron-neutron logging was developed based on an analytical software package designed for channel structure scanning. Its sonic tool was fitted with ^{252}Cf fast neutron source. Neutron-neutron logging was performed in each of the three inspection channels. It has

***Table 2.** Key characteristics of the monitoring system enabling to measure the water content and void formation in RW SF EI-2*

Parameter	Water content	Voids
Method	Neutron-gamma logging	Neutron-neutron logging
Neutron source type	Pulsed neutron generator MFNG-601	^{252}Cf
Detector type	$Bi_4Ge_3O_{12}$ (BGO)	Neutron counter
Effectiveness (measurement range)	2–100%	Empty layer thickness not less than 0.15 m (may be changed)
Measurement uncertainty	40%	–
Penetration depth, m	Up to 40	
Operating temperature, °C	In the range between + 5 and + 35	

***Table 3.** Findings of the neutron-gamma logging performed in the inspection channel № 2 located inside ShT-2 EI-2*

Control station	Depth, m	Material around the borehole	Water content, % mass.
1	24.50	Barrier material	2.26
2	23.80	Barrier material	3.29
3	23.10	Barrier material	3.63
...	...	...	...
33	2.10	Barrier material	3.76
34	1.40	Barrier material	3.67
35	0.70	Barrier material	3.81

Figure 9. Assembling and setting up the neutron-gamma logging complex (left); implementing neutron-gamma logging via an inspection channel at RW SF EI-2 (center); implementing neutron-neutron logging using an inspection channel at RW SF EI-2 (right)

been demonstrated that no significant abnormal density distributions inside the barrier material layer and no voids at the level of the storage facility exist.

Thus, these investigations have proved that the methods developed to monitor barrier material parameters and relevant equipment can be adopted to monitor RW SF EI-2. However, relevant procedural framework and its certification should be primarily developed. Monitoring of these parameters will enable to identify relevant alterations in the barrier materials and timely respond to them.

In addition to engineered barrier monitoring performed using the inspection channels inside RW SF EI-2 via neutron-neutron and neutron-gamma logging, the following types of monitoring are planned to be arranged at the site:

- protection screen monitoring by means of visual inspections and GPR surveys;
- monitoring the position of building structures of the reactor pit and reactor metal structures (leveling) by means of a system of fixed frames and deformation marks;
- monitoring the level of ground water inside the drainage system, their radionuclide and chemical composition implemented using the drainage wells system (visual inspections and measurements) and radiochemical analysis of water samples.

Adequate assessment of RW SF EI-2 impact on the radiation environment of the site requires a comprehensive investigation of initial radiation and chemical composition of soils and ground waters. Environmental engineering survey of the site will enable to clarify the requirements to the contents and scope of monitored parameters and relevant methods.

Conclusion

Constructed RW SF EI-2 is considered to be the only currently available facility providing unique experimental evidence on safety criteria and quantitative parameter values resulted from the research performed and considered in the ENTOMB decommissioning designs. This means that a comprehensive monitoring system should be put in place to evaluate the state of RW SF barriers and its impact on the environment. This should involve systematic monitoring of some key parameters.

In 2016, final engineering and radiation survey of the RW storage site was performed to investigate the facility established following PUGR EI-2 decommissioning. It has been demonstrated that as-built facility complies with the design provisions.

Monitoring performed in 2016 – 2017 revealed that RW SF EI-2 produces no statistically significant impact on the values and dynamics of monitored parameters.

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