RADIATION SITUATION AND ITS EVALUATION WHILE MAKING AN OPENING IN THE UPPER STRUCTURES OF A SHUTDOWN URANIUM GRAPHITE REACTOR

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This article presents the results and methods allowing to evaluate the changes in the radiation situation during the experimental implementation of graphite stack dismantlement methods at ADE-5 PUGR (JSC PDC UGR site). It considers the approaches proposed to limit the increasing gamma radiation levels at work places when an opening is arranged in the upper structures of a shutdown uranium-graphite reactor providing access to the graphite stack and evaluates their effectiveness.

Keywords: *decommissioning, dismantling, radiation fields, uranium-graphite reactor, gamma radiation, radiation factor, radioactive waste.*

Introduction

At present, immediate dismantling option is seen as a priority decommissioning strategy for power reactors of RBMK, AMB and other types in the Russian Federation [1—3]. This approach has a number of undoubted advantages associated with significant savings since long-term maintenance of the facility is not required, highly qualified personnel and critical knowledge about the facility are available early after its final shutdown. It also excludes undue burden placed on future generations associated with radioactive waste (RW) management. At the same time, it should be taken into account that this strategy is difficult to implement, since the main reactor structures are characterized by rather high gamma-radionuclide levels.

The influence of this radiation factor:

- complicates the dismantling process from an engineering point of view since it requires the use of sophisticated remote equipment;
- necessitates the use of additional engineering flowcharts and structures to provide the radiation safety of decommissioning and RW management operations;
- entails high risk of exceeding the permissible radiation doses for personnel.

Taking into account the complexity of the task and the risks associated with this strategy, R&D is implemented in a staged manner to develop and test safe UGR dismantling methods based on the production uranium-graphite reactor ADE-5 (JSC

PDC UGR). The R&D involve extraction and analysis of PUGR structures, their elements and fragments, as well as those of the biological protection [4—6].

At the same time, special attention is paid to the measured activity of structures and changes in the distribution of the equivalent dose rates (DER) at different decommissioning stages allowing to predict the radiation situation and obtain initial data needed to select appropriate methods that would minimize the gamma radiation levels, as well as to assess the radiation exposure of personnel [7] and the opportunities for the operation of electronic equipment constituting to manipulators or robotic systems.

Radioactive contamination of reactor structures, its features and impact on the radiation situation in UGR structures

During the initial cooling period, the gamma radiation DER in metal structures (MS) of shut down production and power uranium-graphite reactors can reach 100 Sv/h. However, with time it decreases exponentially due to relatively short half-life of gamma-emitting radionuclides (^{125}Sb, ^{54}Mn, ^{65}Zn, etc.) contained in the materials of reactor MS. In 10 years, the activity of these radionuclides decreases dramatically and the change in DER becomes more uniform obeying the ^{60}Co decay dynamics.

Table 1 presents the list of key gamma-emitting radionuclides contained in structural elements of uranium-graphite reactors of various types and governing the spatial distribution in terms of gamma radiation field intensity in the reactor space (RS) after this time period is expired.

Figure 1 shows typical distribution of gamma radiation intensity indicators in the PUGR volume measured by the gamma-scanning method [8]. It can be seen that its maximum level is observed in the lower MS from the base plate of the OR layout. High radiation intensity was also recorded in the side (from the casing to the L layout) and upper MS. Complete data on DER measurements for the

Table 1. List and characteristics of gamma-emitting radionuclides in UGR structures responsible for the radiation situation in the RS after 10 years of cooling (PA is an activation product, FP is a fission product)

Nuclide	Source of origin	$T_{1/2}$, years	Gamma energy, keW	UGR structures (elements)
^{60}Co	PA	5.27	1173.22; 1332.51	Steel and aluminum metal structures (elements), thermocouples, graphite blocks, etc.
^{137}Cs + ^{137m}Ba	FP	30.17	661.6	Graphite blocks contaminated with fission products
^{94}Nb	PA	$2.03 \cdot 10^4$	702.6; 871.1	Zirconia elements
^{152}Eu	PA	13.5	121.8; 244.7; 964.08; 1085.87; 1112.07; 1408.01	Aluminum elements, backfilling
^{154}Eu	PA, FP	8.60	123.07; 247.93; 723.30; 873.18; 996.29; 1004.76; 1274.43; 1596.48	Aluminum elements, backfilling, graphite blocks contaminated with fission products

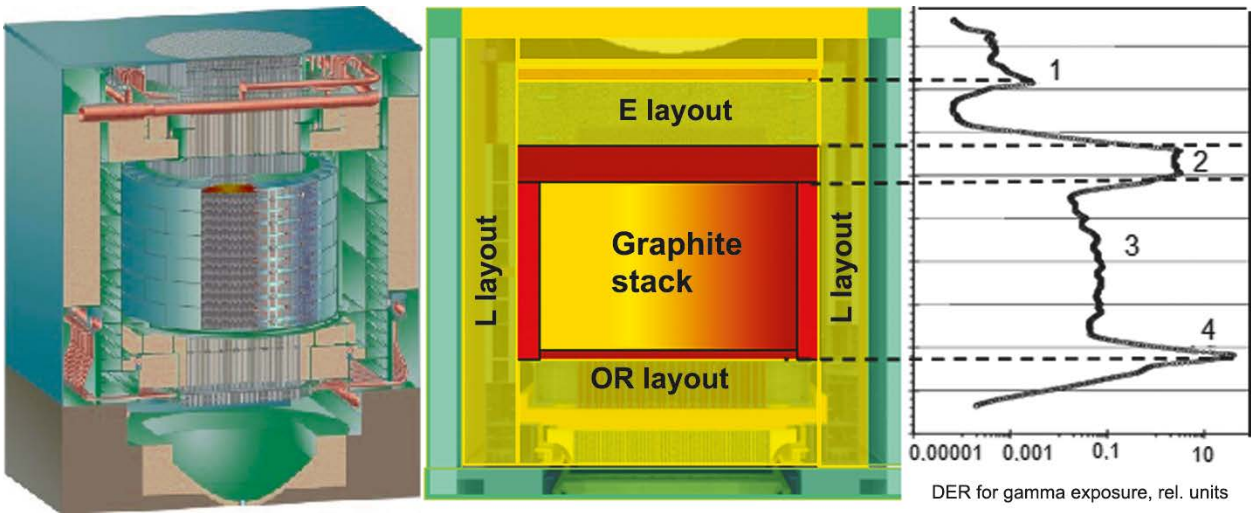

Figure 1. Distribution of gamma radiation in the PUGR structures: on the left, the reactor layout; in the center — reactor layout with maximum DER levels indicated in red; on the right — typical distribution of DER in a loop along the height of the structures (1 — upper utilities, 2 — space between the bottom plate E and the graphite stack; 3 — graphite stack; 4 — base plate OR)

L layout (water protection tanks) are currently not available.

Thus, MS and the structures constituting to the tracts surrounding the reactor core and located in the area between the graphite stack, the upper, lower and side biological shields are mainly contributing to the dose rate in PUGR RS. ^{60}Co is seen as a predominant and dose-forming radionuclide in the material of these structures (carbon and stainless steel, aluminum alloys), elements and some individual parts (Table 1). Gamma radiation spread outside the reactor is limited due to its absorption in the load-bearing structures (E, etc.) and materials of the biological protection (backfill, etc.).

It should be noted that in some cases, in addition to MS, the graphite stack may largely contribute to the gamma radiation levels and the shape of its spatial distribution. This situation is typical for UGR given high local contamination levels with ^{137}Cs governed by its distribution zone due to fuel component spread into the stack [9, 10]. Moreover, ^{137}Cs can greatly contribute to radiation fields emitted by the MS (especially the lower ones) available in the area of a fuel component plume released due to incidents.

Radiation situation in structures depending on the dismantling option and engineering approaches applied

To dismantle the reactor structures, access to the dismantled elements of the installation should be provided, as well as a flowchart for their removal from the RP. This circumstance provides for (depending on the chosen option) the dismantling and removal of individual sections or integral elements of the surrounding reactor structures, including some part of the biological protection, which may result in an important increase in the gamma radiation exposure at the work site and/or in nearby areas. Thus, the choice of an adequate dismantling option is considered an important task contributing directly to the radiation situation and the specific features of the dismantling process.

To develop universal technical solutions for UGR graphite stack dismantlement, a comparative analysis of various options was performed (Figure 2), including:

- option 1: access to the graphite stack is arranged from above by complete dismantling of the upper MS (designed for AMB reactors) [11];
- option 2: access from above with a relatively small opening provided in the upper MS (diagram E) [12, 13];
- option 3: access from a side providing for an opening in the side MS (diagram D).

Advantages and disadvantages of the above options were evaluated and its was found that option 2 [12] proposed by JSC PDC UGR and JSC NIKIET for the dismantlement of PUGR graphite stack and other UGR types can be considered as a most preferable option.

Advantages of option 2 can be summarized as follows:

- a small amount of preliminary work (dismantlement of E layout and utilities only in the area of the opening);
- common flowcharts and equipment can be used in the operations performed in the RS (access from above, insertion and extraction of tools, supply of working media, lighting, power supply, local air suction, use of standard lifting mechanisms, etc.);
- the main premise and its equipment (the central hall of the reactor) are maximally adapted to remote methods used to perform operations in the RS and manage the removed RW;
- personnel can work in the immediate vicinity of the opening;
- low degree of RS depressurization;
- high level of shielding in the access area to the graphite stack from the bulk of activated reactor structures;
- optimal distance between the dismantling station and the extraction station used to remove graphite blocks and fragments of other structures from the RS.

In addition to the engineering aspects, the choice of an optimal dismantling option should be

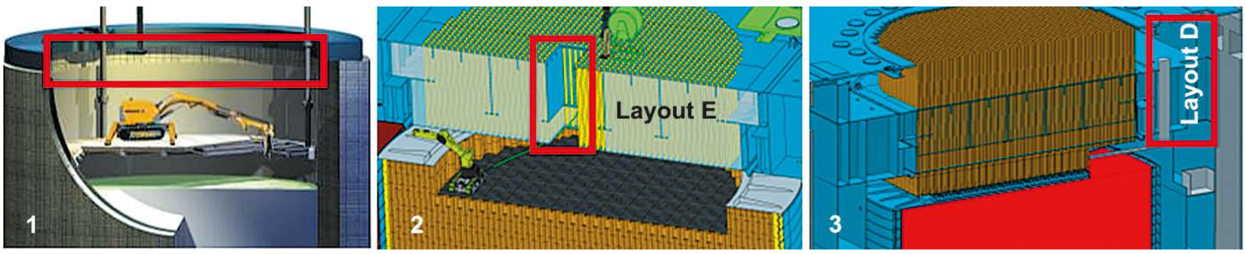

Figure 2. Graphite stack dismantling options: 1 — access from above assuming complete dismantling of layout E; 2 — access from above with an opening arranged in layout E; 3 — access from the side with an opening arranged in layout D. The red frame shows the areas with structures dismantled to provide access to the graphite stack

governed by the radiation factor which is seen as a key factor. Therefore, preliminary evaluated were also the changes in the radiation situation under various UGR dismantling options. These were calculated using an object-oriented software package GEANT 4 [14, 15]. Figures 3 and 4 show the simulation results for options 1 and 2 (gamma radiation plume and its spread are shown in green). ^{60}Co was chosen as the main radiation source in the simulation (Table 1). To calculate option 2, the model also assumed a case when the main contribution to the DER from gamma radiation sources (the upper slab in layout E or the floor level of the central hall — CH) at the workplaces is made by the structures located above the graphite stack (lower flange connections, etc.), and after their removal — by the top graphite stack layer. For option 2, modeled was a method used to arrange an opening: part of the backfill (a mixture of iron ore concentrate and cast-iron shot in the form of a sintered monolith) located only in the lower layers, was left in place all throughout the length of operations associated with the arrangement of an opening and continued to act as a radiation protection barrier. Increased DER could be caused only by the passage of some radiation exposure through narrow penetrations along the contour of the opening. At the same time, to reduce the load produced on the lifting mechanism in the CH during the removal of segments with sintered backfill, considered was the effect produced on the changes in the radiation situation due to its reduced thickness. Backfilling options with a backfill thickness of 40 and 80 cm were modeled as well (Figures 3 and 4).

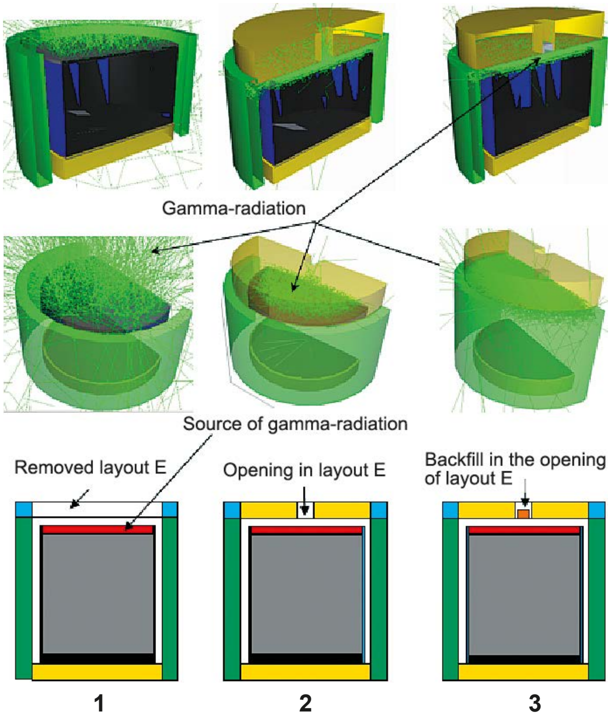

Figure 3. Calculation models used to forecast the changing gamma radiation intensity considering various scenarios for the arrangement of an access to the graphite stack: 1 — the upper biological protection is completely removed (option 1); 2 — access from above with an opening arranged in layout E (option 2); 3 — access from above with an opening arranged in layout E, but at the same time part of the backfill remains in place throughout the length of the operations (intermediate stage of option 2) [13]

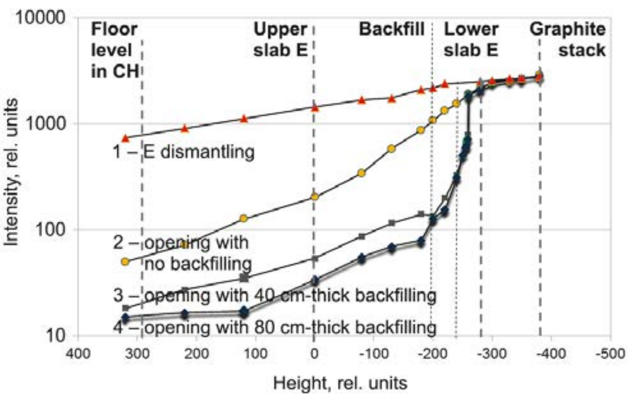

Figure. 4. Forecasted changes in the gamma radiation intensity along the height of the opening (in the center) considering various options and scenarios (1, 2, 3, 4) providing access to the graphite stack

Figure 4 shows height-based DER distributions over the graphite stack considering option 1 (curve 1) and option 2 (curves 2, 3, 4) at various stages of the process constituting to the arrangement of a narrow opening in the upper MS. For a backfilled opening, DER levels were calculated by the height of the opening along the perimeter of a penetration (see Figures 9 A—D), from which the backfill had been removed.

Option 1 can be considered as a most unsafe one for UGR, i. e., since in this case, the upper biological shielding, which provides radiation protection in the central hall (layout E), is assumed to be completely dismantled. Therefore, at the floor level of the CH, DER will increase significantly practically reaching the levels of gamma radiation DER considered typical for the upper MSs (the lower slab is graphite stack). DER will drop by only 5—6 times due to the distance.

As compared to option 1, option 2 limits the growth of gamma radiation DER at the work place in a considerable way by maintaining the protective function of layout E (Figures 3, 4). Gamma radiation may be released only through a relatively narrow aperture. At the same time, if a backfill layer of 40—80 cm is maintained while the penetration is arranged and until the removal of the most active elements (flange, etc.), the growth of gamma radiation intensity at the level of the CH floor may be limited additionally. Also, additional measures can be implemented for the opening (protective cover, etc.) to limit the radiation growth. It should be noted that, taking into account significant uncertainties at the time of the calculations, the error of the results can reach ±80%, which can be considered acceptable for the preliminary assessment of the proposed engineering approaches and their effectiveness.

Despite the fact that option 3 may appear the best in terms of the radiation situation provided at the work site (top of the side MSs), absence of a significant increase in DER at the MS depressurization site (layout E), limits its applicability due to technical difficulties associated with the remote access that should be provided to the dismantled UGR elements and structures. Therefore, this option has not been evaluated under the current study.

Radiation situation at different stages of the experiment on debugging a UGR graphite stacks dismantling method

Despite extensive modeling opportunities, somewhat realistic picture of the changing radiation situation at UGR may be only provided through direct measurements in the RS performed during the dismantling operations, since spatial distribution of gamma radiation intensity at each point is governed by the superposition of radiation fields from several sources of different composition (steel, aluminum, graphite, etc.), spatial arrangement, geometric configuration and specific activity characteristics. At the same time, when a process flowchart was developed for a real-life facility (in our case, PUGR ADE-5), they could be removed in a staged way and, accordingly, their contributions could be estimated more precisely.

In particular, this can be illustrated by the example of a space region bounded by the upper slab of the graphite stack and layout E. Figure 1 shows that in this area DER exceeds the one characteristic for the adjacent structures (graphite stack and layout E) by more than an order of magnitude, which is explained by the fact that in this region (Figure 5) radiation is spreading in the air, i. e., the attenuation characteristics are minimal. In turn, the main radiation sources involve activated metal parts and structures, in which ^{60}Co accumulation is essential (see Figure 5).

Most activated steel structural elements were marked in red on Figure 5, which is due to the higher content of ^{59}Co impurity in steel compared to aluminum. Table 2 shows the calculated specific activities of gamma-emitting radionuclides in samples of individual parts and structures obtained during their extraction from the RC. Also, their density and mass have an important impact on the intensity of gamma radiation emitted by these elements.

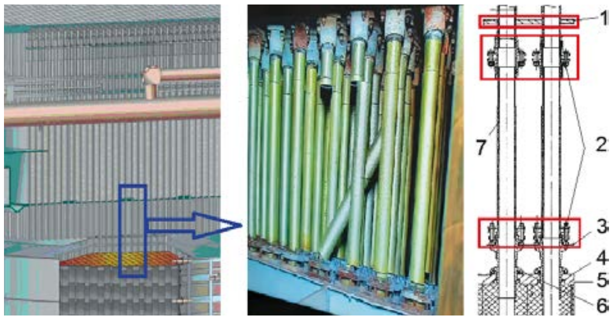

Figure 5. The area between the bottom plate of layout E and the graphite stack of ADE-type PUGR (on the right):
1 – the bottom slab of layout E; 2 – flange connection;
3 – the top sheet of the nitrogen collector's roof;
4 – bottom sheet of the nitrogen collector's roof;
5 – a sheet of slab flooring; 6 – nitrogen collector's pocket;
7 – pipes of the tract (early in the dismantling process)

Table 2. Isotopic composition and specific activity of some parts and structures in the space between the bottom plate of layout E and the PUGR ADE-5 graphite stack (~10 years after the final shutdown)

<table>
<tr><th rowspan="2">Part/construction type</th><th rowspan="2">Material</th><th colspan="4">Specific activity, Bq/g</th></tr>
<tr><th>^{60}Co</th><th>^{137}Cs</th><th>^{152}Eu</th><th>^{154}Eu</th></tr>
<tr><td>Bottom slab in layout E</td><td>Stainless steel</td><td>10^5–10^6</td><td rowspan="4">10^5–10^6</td><td rowspan="4"><10</td><td><10</td></tr>
<tr><td>Slab flooring</td><td>Aluminum</td><td>10^4–10^5</td><td>10^2–10^3</td></tr>
<tr><td>Nitrogen collector's pocket</td><td>Aluminum</td><td>10^4–10^5</td><td>10^2–10^3</td></tr>
<tr><td>Flange connection</td><td>Stainless steel</td><td>10^5–10^6</td><td><10</td></tr>
</table>

Figure 6 shows photographs of the radiation measurement process. In addition to standard dosimetric measurement tools (DKS-AT1121, MKS-AT1117M, etc.), a software-analytical complex (PAK) was used to evaluate changing DER distribution in the experimental area at ADE-5 PUGR. The PAK was developed jointly with OOO GREEN STAR TECHNOLOGIES (Moscow). PAK (photos C and D in Figure 6) includes: a scanning unit (a device used to lower and raise the detector, etc.) and a remote-control unit (industrial laptop with software). The scanning unit was installed directly into the work area above the cell (or penetration). The process was controlled remotely via a control unit equipped with specialized software (Figure 6) that could be used to set the scanning step height-wise. To record the dose rate of gamma radiation, a BDMG detection unit based on Si-pin point silicon detector was used. PAK is the latest generation of previously

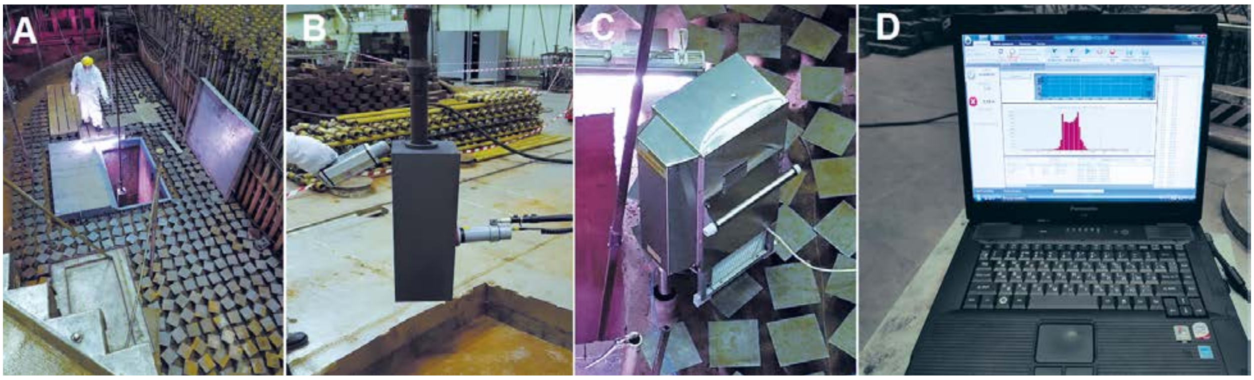

Figure 6. Radiation measurements: A — in the process of graphite block removal; B — measurements of the removed graphite block; C — PAK scanning unit installed at the penetration boundary in the process of gamma radiation DER scanning; D — PAK control unit software interface

developed scanning devices SKU-P, SKU-N and Gamma-R [8].

PAK (Figure 6) was used to scan gamma radiation DER along the penetration height at various stages in the arrangement of the opening (Figure 7). To obtain more complete information, measurements were made in different parts both directly in the opening (in the corner and in the center) and along its outer perimeter.

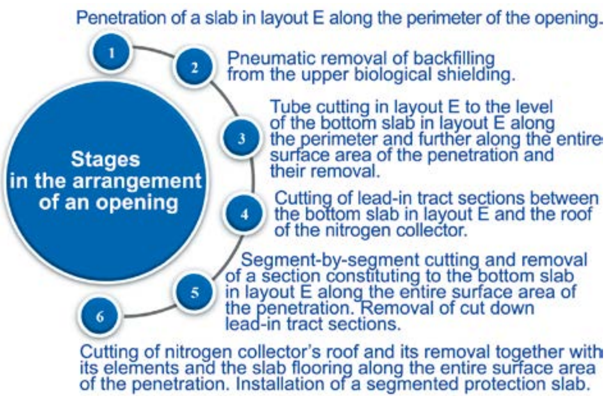

Figure 7. The main stages in the implementation of a method used to arrange an opening required for the dismantlement of a graphite stack constituting to a shutdown uranium-graphite reactor

Figures 7—9 present the main stages in the implementation of a method used to arrange an opening (penetration) required for the dismantlement of a graphite stack constituting to a shutdown uranium-graphite reactor [13].

In the space between the bottom slab in layout E and the graphite stack, MS fragments located over the entire area of the space are considered the main sources of radiation (dose rate ranges from 1 to 10 Sv/h) (Figures 1 and 5, Table 2). Superposition of gamma radiation fields results in a characteristic spatial DER distribution (Figure 10) with two maxima (peaks). Steel MS elements contribute to the greatest extent to the DER at these levels (B, C, D), namely: the bottom slab in the layout E, flange connections of the tract lead-in section, fasteners for flange connections, partially lateral MS (Figures 10 and 5).

Figure 10 shows gamma radiation DER distribution along the height of the penetration at various stages of operations performed to arrange an opening in the upper MS of PUGR ADE-5.

Comparative analysis of calculated and experimental distributions shows that in Figures 4, 10 and, in general, the dynamics in the decreasing gamma radiation intensity are quite similar. At the same time, in Figure 10, the decrease is sharper, which can be explained by the strong influence produced by activated structures directly in layout E (bottom slab and top flange connections).

The trend in the height-wise DER distribution in the space between layout E and the graphite stack, shown in Figure 10 demonstrates the following:

- after the opening is arranged and the biological protection backfill is removed from its volume in Layout E (H — in the range of 0.25—0.50), observed is an insignificant increase in DER compared to the maximum values. These are significantly lower at the level of the upper slab in Layout E where the opening was arranged (by ~ 10^3 times) than in the space between the lower slab and the graphite stack. Thus, a 2 × 2 m opening in the geometry of the upper MSs demonstrates a pronounced effect of "cut down" radiation fields emitted by powerful extended gamma sources under layout E being of ~ 10 m in its diameter;
- when the segment of layout E and the elements located underneath it are removed, the gamma radiation DER peaks caused by the radiation coming from the bottom slab in layout E, the top and bottom flange connections constituting to the lead-in section of the duct are smoothed and disappear (line 3 in Figure 10). At a given high-altitude section,

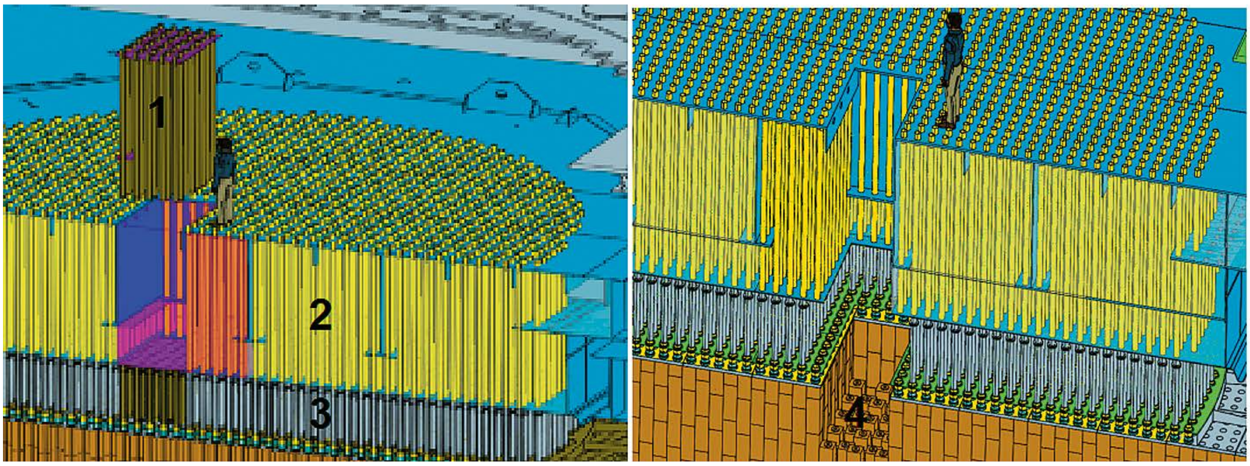

Figure 8. Schematic diagram showing the arrangement of an opening providing access to the graphite stack: 1 — the extracted fragment of layout E; 2 — layout E; 3 — the area between the bottom slab in layout E and the graphite stack; 4 — stack section with removed graphite blocks

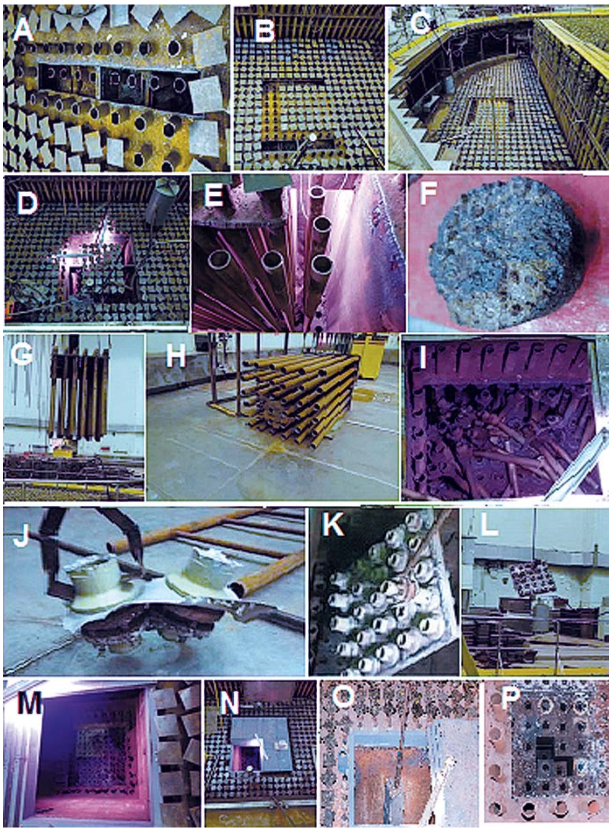

Figure. 9. Main stages in the arrangement of an opening providing access to the graphite stack in layout E: A, B, C, D, E, F, G, H — contouring, backfill removal along the contour and cutting out of a segment in layout E; I, J, K, L — removal of elements constituting to the nitrogen collector tracts and roof; M, N — segment-based protective cover; O, P — part of the upper graphite blocks removed through the opening

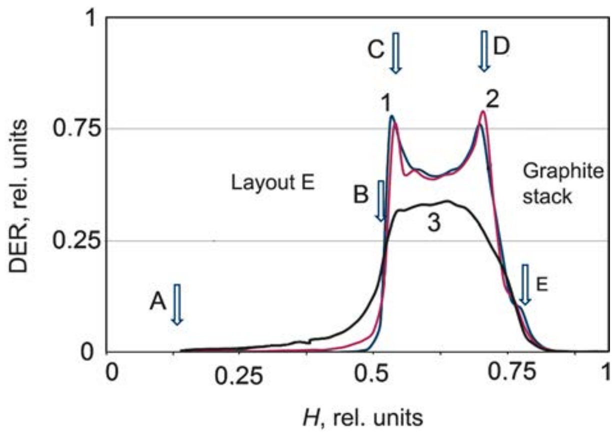

Figure 10. Distribution of gamma-radiation DER along the opening height H at various stages of its penetration in the upper MS of PUGR ADE-5: 1 — before the opening was arranged; 2 — in the process of opening penetration and backfill removal; 3 — after the opening was arranged; A — top slab in layout E; B — lower slab level in layout E; C, D — flange connection levels; E — level showing the beginning of the graphite stack

average DER also decreases by several times as well (with H being in the range of 0.50—0.75).

At the same time, even despite a distance of no more than 3 meters, due to the "cut-off" effect, only ~1.5 % of the gamma radiation intensity reaches the upper structures (H — above 0.25) contributing to the non-exceedance of dangerous dose levels for personnel given the compliance with radiation safety rules (limited work time) or additional protective measures (installation of a protective structure) being in place.

Testing the electronic elements of a robot in RS

To demonstrate the impact of radiation factor on the performance of a mobile robotic complex (MRC) under real-life conditions (gamma radiation DER of up to 1.5 mSv/h, gamma rays energy corresponds to ^{60}Co, air temperature falls within the range of 20—25 °C), stand tests were performed with the electronic elements of equipment (cameras of various types, motors of manipulator units, servo drives,

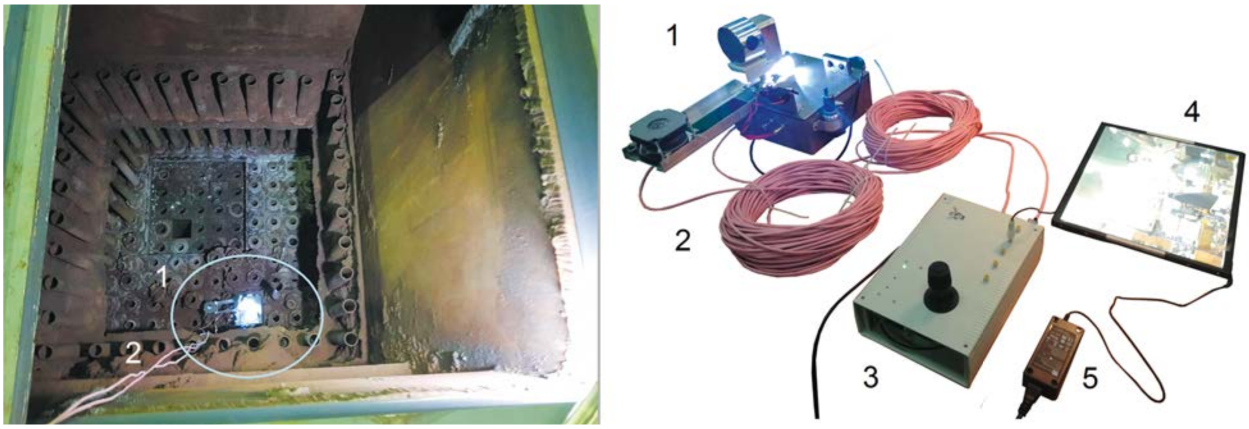

Figure 11. Stand during the testing of MRC electronic elements affected by ionizing radiation in UGR MS:
1 — stand with an element base; 2 — cable; 3 — control panel of the element base; 4 — tablet; 5 — tablet power supply

boards, etc.) being tested as well under hard ionizing gamma radiation (gamma photon energy 1,172 and 1,332 keV) in the MS PUGR (space between layout E and graphite stack). Of particular interest was to evaluate under real conditions the potential application of inexpensive high- and low-resolution cameras originally not designed by the manufacturer for these operating conditions. Stand testing also involved some manipulations performed to remove the graphite block: the stand was held in the opening all throughout the test duration and its performance was checked on a daily basis.

Tests of the stand (Figure 11) with an element base (developed by OOO SKTB PR, Moscow) in the upper MSs showed that basically the MRC element base can withstand dose loads of up to 1.5 Sv/h for two weeks. During these two weeks of testing, only some issues with a rotating high-resolution digital camera were recorded. After a two-week period, signal transmission from the video camera started to slowdown, some noise appeared on the image (“snow”) and, ultimately, the camara broke down completely due to the radiation exposure. In principle, this problem can be addressed by the use of expensive radiation-resistant video cameras or by frequent replacement of the cheaper ones.

Effectiveness of gamma radiation dose rate reduction measures

All operations and methods tested by JSC PDC UGR comply with the international ALARA principle, also involving the minimization of time required to perform the operations under radiation exposure, the use protective tools, increasing the distance, etc. Optimization required to minimize the exposure dose of personnel was also recognized as a must in the recommendations of the International Commission on Radiation Protection ICRP [16]

The unique experience gained was evaluated to assess the effectiveness of measures and engineering approaches proposed under the first stage of UGR dismantlement Arrangement of an Opening in the Upper MS Providing Access to the Stack (Figure 12). Efficiency was calculated: radiation exposure levels were compared for two options, namely, if the measures were implemented or not.

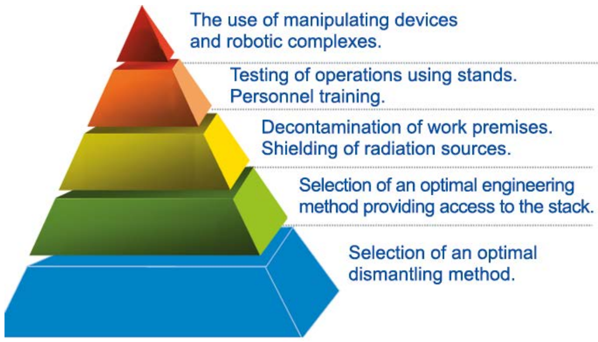

Figure 12. Basic measures (approaches) aimed at reducing the radiation factor impact at the first stage of UGR dismantlement

Application of manipulators and robotic complexes

As can be seen from Figure 12, at present stage, the minimum efficiency is associated with the use of MRC, which is due to the non-standard topic being addressed and the lack of ready-made engineering solutions designed for MRC cutting at the initial stages of research. Most part of the work was performed by personnel using long tools. At the same time, each operation was accompanied by the use of new equipment selected and adapted taking into account the emerging technical problems. MRC were essentially used due to the tests required to check whether its use is possible under real-life conditions and to adapt part of the tools to the dismantling tasks at hand. The MRC was mainly used to dismantle metal elements in the

Figure 13. Collection of tract fragments, cutting of the nitrogen collector's roof using MRC-28

space between layout E and the graphite stack (Figure 13). At the same time, the experience supported the development of plans regarding its wider application in a similar operation to be performed in UGR.

At subsequent stages, the effectiveness of manipulators and robotic systems may only increase along with the increasing length of their use in intense radiation fields (graphite stack dismantlement, etc.).

Development of process operations and tools based on mock-ups and personnel training

The operations performed showed that their effective implementation in cramped spaces required certain qualifications of the personnel operating MRC having proper skills needed to arrange remote control via video communication or interactive 3D imaging of the workspace. Testing of process operations and tools on mock-ups and staff training can significantly reduce the work time, avoid unjustified equipment failures and, accordingly, minimize the time required for the personnel to stay in an area with increased radiation levels.

For this purpose, JSC PDC UGR manufactured a special mock-up representing the upper MS of the reactor and the top layer of the graphite stack. Moreover, to work out the experimental capturing of graphite blocks, a full-size mock-up was constructed providing layer-by-layer simulation of PUGR structures [10].

Decontamination of work premises and shielding of sources

Work places should be decontaminated (in our case, on the upper flooring in layout E) to minimize the radiation levels. Therefore, after the upper group of collectors and pipes constituting to PUGR ADE-5 layout were removed and before its MC and process channels were started being dismantled, the surface of the upper slab was decontaminated, which reduced the dose rate of gamma radiation (DER) at a distance of 1.0 m from its surface by ~ 3 times (from 0.8 to 0.25 mSv/h).

Selection of an optimal engineering approach providing stack access

Prior to the arrangement of a penetration in layout E, gamma radiation DER measured in the testing area was found to be equal to ~ 0.2 mSv/h. When fragments constituting to the lower slab in layout E were removed and the space underneath it along the area of the arranged opening was cleared without the use of additional radiation protection measures (backfilling, protective cover), the DER over the penetration could exceed 25 mSv/h, but if the protective cover was installed, DER did not exceed the initial level of ~ 0.2 mSv/h. At the same time, as previously noted (Figure 4) due to the backfill partially available on the lower slab of layout E before the structure segment was removed, a 10-fold increase in DER (on the upper slab) along the perimeter (in open spaces) could be avoided. Directly above the opening, the DER could increase only insignificantly. Thus, arrangement of an opening according to a purposely developed flowchart (Figures 7—9) allowed to reduce the personnel exposure by at least 10 times.

Selection of an optimal dismantling option

If compared with option 1, selection of an optimal option with the "dismantlement provided through an opening assuming the use of additional measures" generally allowed to reduce the DER by at least 1,000 times, i. e., to a level considered acceptable for the execution of relevant operations by the personnel.

Recommendations

1. Given the current trend for "unmanned" technologies [3] introduced to perform most labor- and dose-intensive operations, it first seems necessary to adapt the tool applied providing its use by robotic systems (manipulators). At the same time, one should keep in mind that JSC PDC UGR specialists should solve a great number of engineering problems directly during work execution due to the lack of ready-made approaches, incomplete information about the structures, backfill, etc. Therefore, application of solely "unmanned" technologies in the dismantlement of RBMK reactor units appears to be impossible until sufficient experience is gained, ready-made technical solutions, tools and equipment are developed and tested. To date, it's recommended to consider robotic complexes as auxiliary means reducing personnel exposure, and due to the upgrading and improvement of relevant approaches, to gradually increase their role and performance under UGR decommissioning designs.

2. Preliminary modeling results and experimental data obtained should be used in the development of

a specialized mathematical apparatus to assess the radiation characteristics of elements (specific and total activity, gamma radiation DER) before these are removed from the reactor.

Conclusion

1. Further prospects of an approach proposed for graphite stack dismantlement through an opening developed by JSC PDC UGR have been demonstrated, as well as the opportunities for its adaptation for other UGR types.

2. Computational and experimental methods used to analyze the changes in the radiation situation during the experimental testing of graphite stack dismantling technologies allowed to gain information required to develop and implement measures reducing the influence of radiation factor at the current stage and supporting further research on the development of dismantling technologies for the lateral and lower MS and the graphite stack.

3. At present time, an opening arranged in ADE-5 PUGR structure provides unique opportunities associated with the equipment testing in real conditions characterized with high gamma radiation levels, which is required to provide the equipment for the decommissioning of various PUGR types, including RBMK, AMB and EGP-6.

4. The analysis showed that the experience gained can significantly increase work performance if similar operations are planned to be executed at various UGR types.

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