RW VOLUMES FROM THE DECOMMISSIONING ESTIMATED USING INFORMATION MODELS

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Article received on August 12, 2020

At present time, intensive efforts on the decommissioning of nuclear facilities are being actively performed with the efficiency improvement viewed as a key task in their planning. Since the management of the generated radioactive waste is considered as a main component of the decommissioning cost, reliable estimates of the generated RW amounts are essential. The paper seeks to demonstrate an approach to assessing the amounts of decommissioning RW based on the data from comprehensive engineering and radiation survey of a facility in question using digital information models.

Keywords: *radioactive waste (RW), decommissioning, building information model (BIM), federal target program, effectiveness.*

Management of radioactive waste (RW) from decommissioning is viewed as a main component of nuclear decommissioning costs. Reliable assessment of RW amounts is considered essential for effective planning and use of financial resources, as well as for the development of RW management infrastructure, including RW disposal facilities. To date, comprehensive engineering and radiation surveys (KIRO) have been completed only for a relatively small number of such facilities that in the future are not expected to be operated according to their original design purpose. Thus, planning efforts are based on basically simplified estimates, in particular, those derived based on an approach allowing to evaluate decommissioning financial liabilities for reporting purposes in accordance with the International Financial Reporting Standards (IFRS). It's worth emphasizing that if these estimates are applied for an entire set of facilities, relevant errors are partially offset by each other. However, if these are applied to individual facilities, large discrepancies can be observed between the preliminarily estimated RW volumes and those actually resulted from decommissioning. Due to these factors comprehensive planning of decommissioning efforts for the nuclear industry in general seems to be a much more complicated task especially taking into account existing budget constraints. Therefore, integrated planning shall be focused on a stage-by-stage refinement of estimated RW volumes for the key facilities awaiting decommissioning in the short- and mid-term.

Initial data for the assessment of RW generation volumes

KIRO is considered as a main source of initial data used to estimate the volume of RW generation and indicating the equipment and building structure contamination level. In part of radiation characteristics, KIRO reports generally present primary information on radiation contamination (measurement points, measured radiation characteristics of elements), as well as the data processing results. Various physical quantities obtained both from direct measurements and using calculation-experimental method can be presented as radiation characteristics of elements: specific activity for individual radionuclides or radiation exposure type (alpha, beta), dose rate of ionizing radiation at a certain distance, particle flux density (alpha and beta), etc. Data processing results may be plotted into contamination cartograms showing various physical quantities measured also allowing to specify the generation volumes for RW and industrial waste with an increased number of radionuclides.

It should be also noted that despite the required presentation of estimated RW generation volumes based on KIRO findings [1, 2], such estimates can be actually provided only based on certain assumptions regarding the purposed dismantlement technologies, decontamination methods and radiation monitoring of facilities and materials. Oftentimes, KIRO does not present such information and it can only be partially reproduced based on indirect indications, which makes it difficult to re-evaluate RW amounts during decommissioning design development if other methods are assumed.

Prior to the introduction of recommendations regarding the development of KIRO program and its implementation (RB-159-19, RB-160-19), no unified approach was applied to its planning and implementation. As a result, both the level of detail and data presentation in the reports varied significantly. Tables 1 and 2 represent the level of detail of KIROs performed for two facilities at two different sites: sublimate production (SP) at AECC site and radiochemical plant (RCP) at SCC site.

Table 1. Statistics of survey data for AECC facility

Building/ structures	Structure volume, m^3	Measurement points		Survey pits		
		floors	walls	walls	floors	soil
327	15,754	260	93	37	16	24
303	82,300	332	-	1	1	17
301	143,600	939	3	3	3	2
320B	4,076	84	260	4	4	14
Gas flues	85,000	446	223	21		38

Table 2. Statistics of survey data for SCC facility

Building/ structures	Structure volume, m^3	Measurement points		Survey pits		
		floors	walls	walls	floors	soil
227	9,016	42	74	-	-	-
201	438,365	873	-	-	-	-
252	364,696	184	-	-	-	-

As can be seen from the data presented above, the level of detail in the KIRO performed for different facilities differs significantly even within the same site. At the same time, high data content in the report providing information on building 327 (AECC site) is not explained by its contamination levels. The main production building (301) at AECC site with its construction volume being an order of magnitude larger than the former one, is characterized with a significantly smaller number of samples (pits) showing the depth of contaminant spread inside the building structures.

Lack of reporting data on the depth of contaminant spread inside the materials of RCP building structures at SCC site is viewed as an obvious disadvantage of the survey performed for this facility. At the same time, such studies were carried out during the examination of SP building structures at AECC site.

In addition, KIRO reports on RCP at SCC site and SP at AECC site provide no data on the position coordinates of the measurement points in the premises. In case of AECC SP these can be reproduced based on cartograms, whereas for SCC facilities the reports provide only a range of measured value fluctuations in different premises or its average value.

Apparently, incomplete data does not allow accurate assessment of RW generation volumes. On the other hand, additional surveys aimed at determining the nature of radioactive contamination, including its distribution over depth are viewed as a very laborious and time-consuming process. An optimal way suggests some reasonable increase in the KIRO level of detail supported by analytical methods enabling adequate assessment of RW volumes and characteristics based on a limited data.

Accuracy of estimated RW volumes generated from decommissioning is seen as a key issue for planning both relevant activities associated with RW management and waste transfer to disposal, as well as the decommissioning of a facility in general. Therefore, evaluation of RW volumes expected to be generated from decommissioning should be supported by uncertainty assessment as regards such calculations. This allows to understand possible variations in the amount of required labor and financial resources. Currently observed deviations between the forecasted and actually generated RW volumes seem to be quite large. Thus, during the decommissioning of research building B at VNIINM site, actual RW volume exceeded the forecasted one by almost 3 times [3], and the difference in the RW management cost amounted to over 1 billion rubles. Reverse trends can be observed as well.

Information models as tools for the assessment of RW generation

Information models (BIM models) representing facilities along with the algorithms designed to restore spatial data on contamination may substantially improve the quality of RW generation forecasts.

Information modeling being considered as a set of modern tools and methods used in the design development of industrial facilities seems to be critically important for decommissioning purposes [4]. Below are presented the main aspects implemented under information modelling the necessity of which has been referred to by the best international practices in nuclear decommissioning. Firstly, it involves the development of a model for each stage of facility's life cycle (LC) and its staged evolution from construction to decommissioning designs (including the preservation and communication of the original design and estimate documentation along subsequent stages of the facility's life cycle). Secondly, it implies preservation of information on the facility being considered important for its operation and subsequent decommissioning, which includes:

- information about normal operation of production processes, as well as malfunctions, accidents and incidents at the facility (the so-called performance history);
- information on performed KIRO and engineering surveys;
- information on changes introduced to facility design and reconstruction of the facility or its sections.

Thirdly, information model being a common data environment for all participants of the decommissioning process is seen a technologically flexible project management tool. This ensures technological transparency of mechanisms allowing to introduce changes to decommissioning designs, control over the construction volume (volume associated with dismantlement operations), availability of data on KIRO and RW generation for the parties involved in the project.

To date, simulation information models mainly addressing the refinement of operations associated with the dismantlement of PUGR stacks [5, 6] and a number of other purposes [7] is seen as a most considerable national experience that has been reflected in literature sources. These activities correspond to international practice on the improvement of dismantlement methods for contaminated nuclear equipment [8, 9]. At the same time, Russian literature sources provide no reference to the problems associated with the assessment of RW generation volumes from decommissioning based on information modeling.

This paper discusses the use of information modeling in the assessment of waste generation during the decommissioning of SP facilities at AECC site providing a solution to a number of problems ranging from the development of an "as built" model of SP facilities (reengineering task) to the development of a 5D model under decommissioning designs.

Such information modeling eventually resulted in a package of digital information models (DIM): BIM No. 1 — laser scanning data model, BIM No. 2, BIM No. 3 — information models presenting different refinement levels as regards attributive information and equipment, BIM No. 4 — 5D model of decommissioning designs.

In 2019, surveys and laser scanning of buildings and structures were performed to refine the data on the current state of facilities and to develop BIM No. 1 and BIM No. 2 for the AECC's SP site. These operations were performed inside the premises containing process equipment and engineering systems. Field surveys and measurements using ground-based laser imaging were carried out using Leica Geosystems RTC360 laser scanner.

Leica Cyclone Register software was used to process the initial laser scanning data. Autodesk software referring to Revit 2019 information modeling environment was used for reverse reengineering (reconstruction based on laser scanning data) and the development of an information model. Moreover, additional software (scripts) was developed to edit the parameters describing the families of elements associated with the unloading model and then to load the customized equipment parameters, surface contamination data, interpolated points of contamination and to build up cartograms of surface contamination in the model. This enabled the automation of processes designed to adjust the attribute data of the model elements, as well as the processes enabling calculations and construction of cartograms representing the contaminant spread.

Information model representing the decommissioning designs developed as the result of comprehensive efforts is a complex 3D model involving key facilities being considered important for the decommissioning, a description of attributive information and KIRO data. The model was developed based on a generally accepted approach applied to identify the level of model development (LOD) [10], involving the level of geometry (LOG) and the level of information (LOI). Refinement of model's geometry is viewed as an essential point when it comes to addressing dismantlement tasks and those associated with the identification of RW generation amounts. Thus, it seems rational that key geometric boundaries for the process equipment subject to further dismantlement should be reasonably specified only under the tasks dealing with visualization and approximate representation of the volume filled with such equipment (Figure 1). Whereas, when it comes to architectural elements (wall, slabs), on the contrary, it seems necessary to present more detailed requirements to the geometry of the model elements — up to an error of 0.1 meters in the discrepancy with the “as built” model (according to laser scanning).

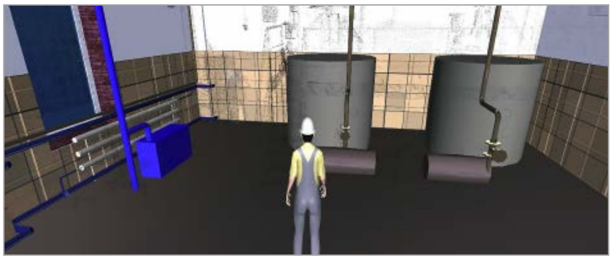

Figure 1. Information model. Level of geometry for the process equipment

The key elements of an information model important in terms of decommissioning include:

a) architectural and structure part of buildings and structures, including: building blocks, marks, layout of premises, load-bearing concrete and metal structures, service platforms, staircases, pipes, process pipe racks;

b) elements of decoration in the premises (plaster, paintwork, facing materials, flooring materials);

c) general utilities, including heating and ventilation systems, water supply and sewerage systems;

d) main electrical power installations and process equipment (Figure 2).

Radiation monitoring elements implemented in the model (“radiation monitoring/ measurement point”, “contamination map”) contain radiation characteristics. These characteristics together with those recorded as part of the attribute data on the model elements allow to calculate the volume of generated RW by waste categories (material, type and category of equipment or architectural element). Information model generates customizable reports: item specifications and statements of decommissioning work scope.

Regardless of the LOG, given rough and heterogeneous radiation environment, as well as insufficient data on the operational history of a facility, the quality and completeness of KIRO findings together with the attribute data of the model elements determine the accuracy of the assessment.

The following steps should be implemented to calculate RW generation volume based on an information model:

a) creation of families representing KIRO elements within the model,

b) semi-automated input of KIRO data into the model,

c) interpolation of KIRO data,

d) construction of cartogram elements based on the data from the interpolation.

At the first stages, measurement data on the contamination levels and the distribution of measurement points in accordance with the cartograms and tables given in the KIRO reports are entered into the model. Whereby each point is assigned with corresponding attributes: serial number, ID-address, alpha-, beta-, gamma-contamination levels,

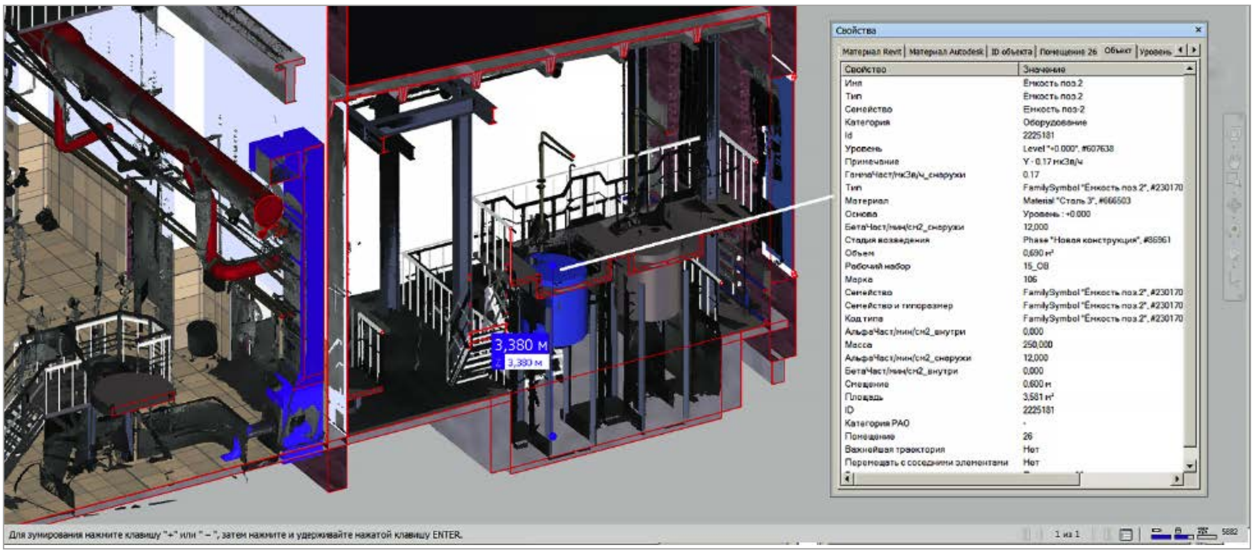

Figure 2. Level of geometry for key facilities considered important for the decommissioning exemplified by a BIM developed for building 327

ID number of the premise. Thus, based on the entered data, arrays of points are generated within the model (Figure 3).

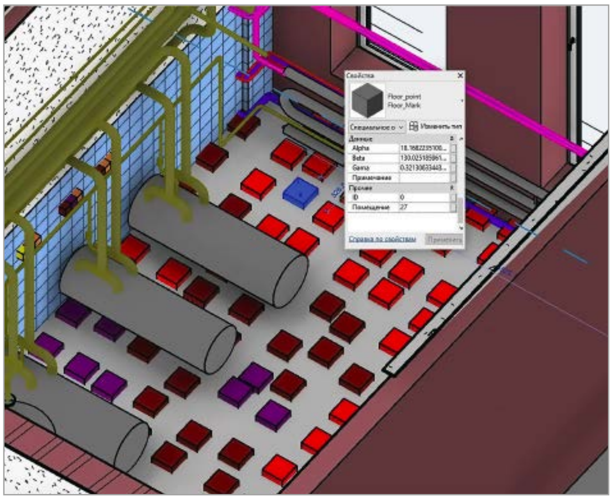

Figure 3. Model representation showing the measurement points for radioactive contamination on the floor

We believe that in the near future KIRO data should be digitized. This means that presentation format for KIRO data (including such elements of the information model as "radiation monitoring/measurement point", "contamination map") should be unified and the standard for the survey procedure should contain uniform description rules within a single environment. The latter one is perceived in the future as a digital twin [11]. This process will greatly affect the so-called digital transformation in indoor radiation survey data processing. First, it will provide an opportunity for an integrated accumulation of KIRO results, i. e. development of a database that technically implements the mechanism of a knowledge management system (KMS) [12]. Secondly, it will increase the accessibility of information to key stakeholders — design organizations, regulatory bodies, contractors and scientific organizations.

Interpolation of KIRO data is required to enable their use during the assessment of RW volumes and characteristics. This need is due to the following factors:

- uneven distribution of measurement points over surfaces, as well as the need for assessing the characteristics and volumes for various groups of radioactive and industrial waste;
- the need to breakdown the RW into groups according to subsequently applied treatment methods and RW characteristics after its conditioning.

In general, various interpolation methods can be applied: these are discussed quite thoroughly in [13]. When choosing the interpolation method, the following features of KIRO results were taken into account under the development of BIM No. 3 for AECC's SP:

- a relatively small number of measurement points in a particular premise (normally some 20 measurements were performed within each premise, however in some premises more than 100 measurements were performed whereas in certain ones this number amounted to only 5);
- presence of punctured (single-point) peaks against the general low-level background;
- uneven distribution of points over the surface.

Physically understandable requirements were imposed on the interpolation results stating that they should not:

- demonstrate the spread of punctured peaks, but at the same time, so that the peaks themselves are neither smoothed out nor spatially displaced;
- form unexpected bursts of increased values, the so-called artifacts. To meet these requirements, a triangular mesh built based on Delaunay triangulation [14] was used for the interpolation.

Using such mesh, all the input data presented in an undistorted form can be incorporated into the result since these are viewed as its nodes. The algorithm allowing to build such interpolation mesh can be briefly described as follows:

- building the original Delaunay triangulation based on a set of source points and room angles;
- calculating the areas of triangles and the average area;
- selecting the triangles with an area greater than the average one and incorporating a new point into each of them being equidistant from all its corners;
- checking for minimality of obtuse triangles and rebuilding the system, if deemed necessary.

7—8 iterations made allowed to achieve a uniform and sufficiently dense interpolation mesh.

For rectangular premises, convex polyhedron coincides with a rectangle built at the corners of the premise, and, accordingly, the entire area of the premise falls into the interpolation region. For non-rectangular shaped premises (L- and T-shaped), the mesh was generated based on a convex polygon (Figure 4) with the unnecessary areas cut out afterwards (Figure 5).

Figure 6 exemplifies the calculations and reconstruction of contaminant spread over horizontal surfaces based on interpolation data.

After being loaded into the information model (without replacing the results of actual measurements), the interpolations generated as shown above allow to develop an extended list of contaminated zones present within the considered facility according to boundary values set by the user.

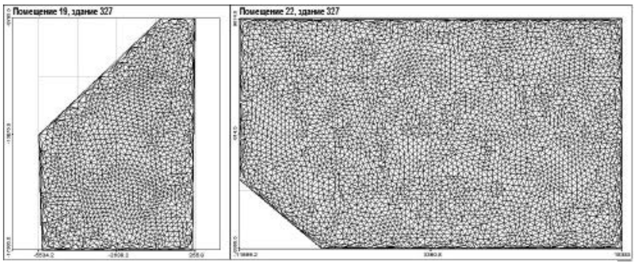

Figure 4. Example of an original triangular mesh generated for L-shaped premises

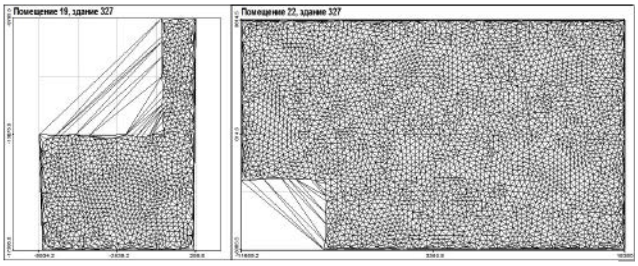

Figure 5. Example of a triangular mesh for L-shaped premises

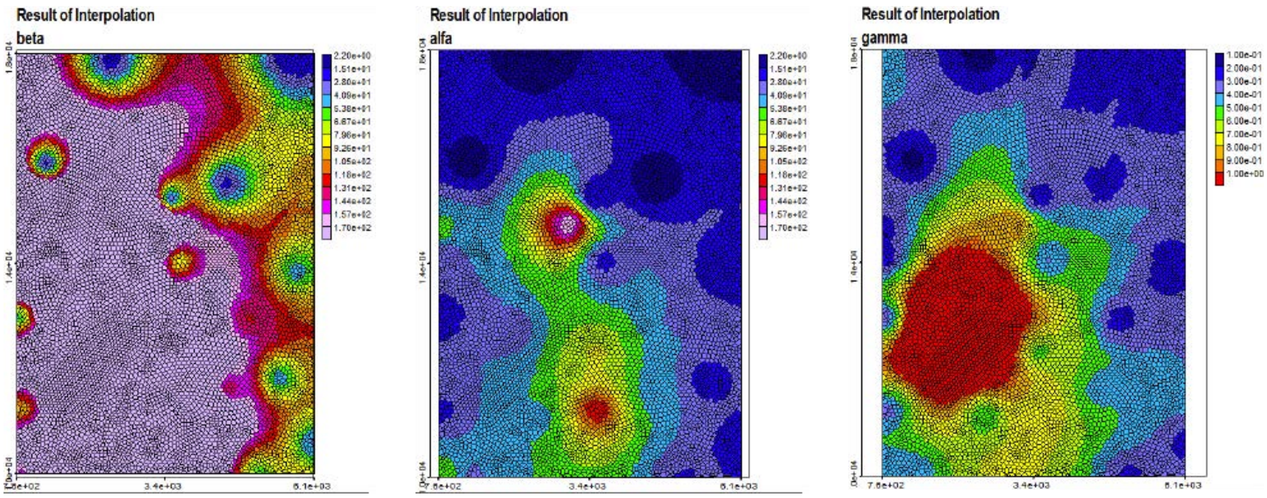

Figure 6. Cartogram of floor contamination with α- and β-emitters and DER

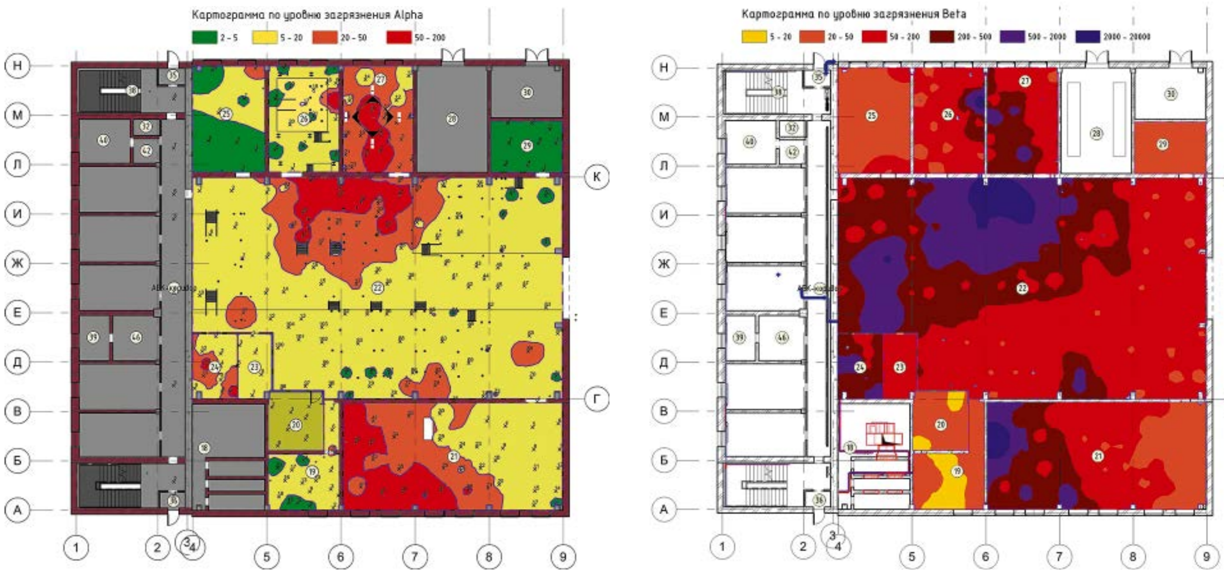

Figure 7. Cartograms of flux density considering α-emitters (left) and β-emitters (right)

It should be emphasized that in case of contaminant cartograms presenting the entire facility the level of correlation between various contamination components increases (Figure 7) as compared with cartograms developed for individual premises (Figure 6).

Inclusion of radiation characteristics into the information model provides not only a significant improvement in the data perception, but also enables their refinement based on additional measurements, if these are performed, and increases the level of data security. Moreover, implementation of a two-tier KIRO planning scheme is seen as another promising application of information modeling. First, we start with the first KIRO stage: a list of necessary additional measurements to be performed under the "refining" KIRO stage is determined based on its findings. Obviously, this can be done only in case of prompt development of information models representing the considered facilities.

Analytical approaches to the assessment of radioactive and industrial waste volumes with an increased radionuclide content

Earlier it was noted that proposed decontamination technologies should be accounted for in the assessment of RW generation amounts. Moreover, to assess the cost of subsequent RW management, waste shall be broken down into groups not according to formal categories being specified based on waste activity (VLLW, LLW, ILW, HLW), but along the boundaries suggesting the application of a certain RW management flow chart. For example, considering the management flow chart for contaminated metal (Figure 8), it seems clear that the following boundaries should be specified: "clean/contaminated metal", "clean/contaminated metal after liquid decontamination", "clean/contaminated metal after pyrometallurgical processing."

To specify relevant boundaries, an indicator should be used according to which the interpolation of KIRO results is done. A relationship should be established between them and the specific activity based on which either the possibility of restricted/unrestricted use or the ultimate RW class in case of retrievable waste is stated. Considering different materials, these boundaries will differ depending on a number of factors: density, decontamination technology (degree of decontamination), type of contamination (surface or embedded), etc.

For these purposes either the corresponding indicators experimentally measured for various materials during KIRO (if measured) or the calculated values can be used. Below is presented a case study of concrete surfaces.

Since embedded contamination is typical for porous materials (including concrete), its cross-section is evaluated at the first stage. For this purpose, data on the contamination of concrete structures measured in AECC's SP pits were systematized with the normalization of the particle flux density over the surface. The normalized results were approximated and their dependence on the sampling depth was determined. In case of a concrete structure, the following expression can be used to describe alterations in the flux density of beta-emitters depending on the sampling depth:

$$F_{\beta} = 1.3e^{-0.6x}, \quad (1)$$

where x is the depth of the measured surface, mm.

At a later stage, taking into account the thicknesses of samples taken and measured specific activity of material, it is possible to determine its dependence on the particle flux density. Figure 9 shows the approximation for the specific activity of concrete depending on the surface contamination obtained based on systematized data from KIRO reports developed for AECC's SP facilities. Data on the flux density of beta-emitters were used as a radioactive contamination indicator since this value is less prone to distortion due to shielding effects.

Boundary values for the metal cladding of building structures can be estimated as a first approximation based on the hypothesis suggesting surface material contamination via simple recalculation of particle flux density into specific activity taking into account the density and thickness of cladding material. Table 3 presents the resulting ranges for the metal cladding.

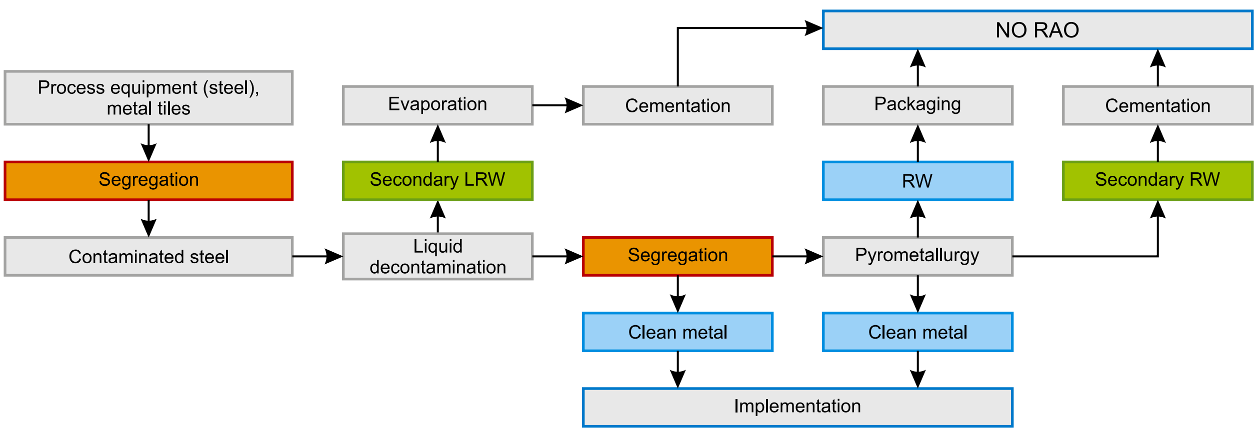

Figure 8. Operation flowchart for metal waste management (equipment and tiles)

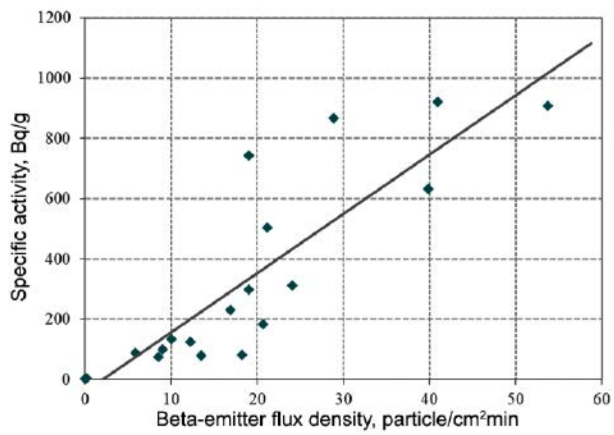

Figure 9. Dependence of specific activity on the flux density of beta-emitters from the concrete surface

Table 3. Boundary values for RW categories (dismantled metal cladding)

Material	Clean/ contaminated metal, particle/cm^{2}min	Clean/ contaminated metal after liquid decontamination, particle/cm^{2}min	Clean/contaminated metal after pyrometallurgical processing, particle/cm^{2}min
Metal	50	20,000	2,000,000

Further on, based on the information model, specifications are drawn using the developed script: they present data on the contamination areas for each material according to the specified boundaries. Then, based on these specifications, the volumes of RW subject to some processing according to a particular processing flow chart are identified.

The above approach is considered applicable only if initial KIRO data allow their interpolation. Otherwise, for example, if only a small number of measurement points is available, such an approach seems to be irrelevant. Considered case study refers to data on the contamination of walls, as well as underlying (with respect to cladding) layers of building structures with only single measurements being available for its premises (in some cases, the data are missing completely). In this case, the task can be addressed by establishing a mutual relationship between the contaminant distributions on the floor surface and other surfaces over a wider set of data (for example, over the entire building) followed by the assessment of contaminant distribution over relevant surfaces based on the measured floor contamination inside particular premises.

For example, if the distribution of measured surface contamination is close to normal, then an approach based on the Laplace function can be applied allowing to estimate the probability with which random normally distributed variable is falling into a given range. This method allows to identify the surface portions corresponding to a given range of contamination.

$$P(\alpha \le x \le \beta) = \Phi\left(\frac{\alpha - \bar{x}}{\sigma}\right) - \Phi\left(\frac{\beta - \bar{x}}{\sigma}\right), \qquad (2)$$

where α and β are standing for the range of contamination values;
$\bar{x}$ is the average floor/wall contamination;
σ is a standard deviation for the contamination value.

Further on, knowing the nature of the interdependence between the two surfaces, the fraction of the surface that will correspond to a given contamination range can be identified. According to the established KIRO practice, data on the contamination of floor surface appear to be presented in much more detail compared to the data on the walls or embedded layers. The origin of contamination on vertical and horizontal surfaces appears to be different. Horizontal surfaces are contaminated due to spills or scattering of radioactive media, vertical ones — due to gas-aerosol impact. Nevertheless, given the long period during which the contamination evolves, routine activities on surface decontamination, as well as gas-aerosol transport of contaminants, there should be certain relationship between the contamination level of horizontal and vertical surfaces in a sufficiently large volume of premises and facilities. Therefore, data on the floor contamination can be used to assess the distribution of contaminants over other surfaces, if relationships between corresponding distributions are identified beforehand. Statistical analysis of KIRO data on AECC's SP shows that, in general, contaminant distributions over other surfaces are similar in their nature, while the walls and underlying layers are characterized with a lower average level of contamination and a smaller spread of values.

Looking back, it should be noted that final RW volumes and characteristics depend on the adopted decontamination and management methods. To develop an optimal system providing the management of RW from decommissioning, an economic analysis should be carried out with due consideration of alternative options. Since the cost estimates should take into account the capital costs associated with the construction of various types of facilities and the cost of actual waste processing, different combinations of technical solutions may be considered optimal as regards different RW volumes and characteristics. If RW volume is small, then either simplified processing methods taking advantage of available facilities can be applied or specialized RW management organizations can be contracted. In case of large RW volumes, construction of advanced processing units at the site seems to be feasible despite of additional construction costs involved.

Therefore, a comparative evaluation considering several options with each one corresponding to particular volumes of RW generation and its characteristics, as well as relevant cost estimates are needed. This challenge cannot be addressed properly without the development of any automatic (at least partially) assessment tools.

Another possible focus area where this set of information and analytical methods can be potentially applied is the assessment of calculation uncertainties. It should be emphasized that in the considered case, this assessment seems to be quite essential. Regression analysis was performed to assess calculation uncertainties based on a study case of crushed concrete RW. It was shown that in case of the calculated volume these account for ~30% which is only due to a transition from particle flux density to the specific activity of materials. But, nevertheless, availability of such estimates can substantially increase the validity of plans. In cases when due to the lack of accurate data a fixed part of building structures (from 100% to 10%) is categorized as RW, it is impossible to speak about the validity of planning decisions.

It should be noted that resulting uncertainties can and should be significantly reduced as the amount of information on the facilities grows both due to additional refining measurements and advancement of decommissioning operations. Here, again, crucial role is devoted to information models: in this case these can serve a basis for the development of databases allowing to accumulate the results and enabling their further processing at all decommissioning stages.

Conclusion

Identification of RW generation amounts and an optimal RW management flowchart is seen as a main task for the pre-decommissioning stage. These assessments should form a basis for design decisions on RW management further being transformed into the plans of the National Operator for RW Management on the development of disposal infrastructure. The need for economic and variant assessment of RW generation amounts indicates the importance of applying both modern approaches and modern tools in addressing the pre-decommissioning tasks.

The method based on information modeling and proposed to assess the volumes of RW generation from nuclear decommissioning can be effectively used in planning and design development. It allows to develop scenarios describing practical implementation of decommissioning operations and not only to predict the amount of RW expected to be generated under each specific scenario, but also to categorize RW given a proposed management flowchart. Practical experience gained from the evaluation of KIRO data on AECC's SP and the development of information models suggests that these two pre-decommissioning aspects should be reasonably considered as complementary to each other with the following recommendations to be taken into account during the surveys:

- information model should be developed at pre-KIRO stage. This allows to streamline the accumulation and storage of data on nuclear facilities. KIRO should be carried out taking into account the information modeling results. For example, information modeling results for buildings 301 and 303 of AECC's SP revealed that radiation measurements performed for the walls of these buildings were insufficient, since with a small number of pits it was impossible to identify the volumetric distribution of radionuclide activities in the materials of structures, systems, elements. These disadvantages can be avoided through the development of a survey program taking into account the data from the information model, including the results of their office processing performed to identify the need of additional measurements;
- development of technical KIRO specifications and KIRO programs should be carried out taking into account the requirements stated in RB-159-19 [2] and RB-160-19 [15].

Appropriate assessments should form a basis for design solutions on RW and industrial waste management when it comes to the assessment of decontamination and RW management labor intensity.

In the future, BIM should become part of a decommissioning database, in which the information from all decommissioning stages is going to be integrated. This will also reduce the uncertainties in the estimated RW generation amounts due to the inclusion of actual data into the analysis, namely, those obtained early in the decommissioning stages. In the future, as information on various facilities accumulates, estimates for other facilities will be refined through the formation of more substantiated statistical hypotheses about the nature of their radioactive contamination and its core factors.

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Aleksandrova T. A., Ivanov A. Yu., Linge In. I., Lunov D. M., Saveleva E. A., Samoylov A. A., Utkin V. B. RW Volumes from the Decommissioning Estimated Using Information Models. *Radioactive Waste,* 2019, no. 3 (8), pp. 36—43. DOI: 10.25283/2587-9707-2020-3-19-31. (In Russian).