REFINEMENT OF KORIDA SOFTWARE COMPLEX AND ITS APPLICATION IN ADDRESSING SNF AND RW MANAGEMENT PROBLEMS

Arakelyan A. A., Blohin A. I., Blohin P. A., Vaneev Yu. E., Kazieva S. T., Kizub P. A., Kondakov V. G., Panchenko S. V., Sipachev I. V.

Nuclear Safety Institute of the Russian Academy of Sciences, Moscow, Russia

Article received on June 24, 2022

The paper overviews current progress in the development of the KORIDA software and some examples of its application providing solution to RW and SNF management problems. Its functional capacity has been greatly extended, in particular, providing automated development of models required to calculate exposure doses to personnel based on laser scanning data, as well as through the development of modules evaluating exposure impact on the population and biota. The paper also presents the results of nuclide kinetics module verification and validation, evaluated doses of potential exposure for the population in the vicinity of a near-surface RW disposal facility.

Keywords: *SNF and RW management, software complex, development of calculation models, calculation results, exposure dose rate for personnel and the public, radioactive waste.*

Introduction

Federal target programs provide for large-scale efforts addressing the challenges associated with the final stages of nuclear facilities' (NF) life cycle (LC), including spent nuclear fuel (SNF) reprocessing, decommissioning of nuclear legacy facilities, radioactive waste (RW) management. New technologies that are rapidly evolving in this area, including the digital ones, and modern requirements for the assessment of nuclear facilities in terms of their nuclear, radiation and environmental safety impose special conditions on the calculation codes and their application at all LC stages.

At the pre-design stage of decommissioning, digital information model development tools and calculation codes can support decision-making on most effective technical and managerial approaches. These decisions are made based on numerical safety assessments considering different alternative options, including the assessment of radiation impacts on personnel, the population and environmental objects both during decommissioning operations and in the long run.

Software package (SP) KORIDA (Software Package for the Radiation Safety Assessment of Facilities with Ionizing Radiation Sources, Dose Aspect) is being developed. It is designed to provide fully fledged radiation safety assessments, including relevant forecasts regarding the radionuclide compositions of irradiated materials, their radiation characteristics and the resulting spatial dose distributions. Information about its structure and functional capabilities at the first stage of its development is given in [1].

Later, the software package was improved with a focus place on:

- verification and validation of the TRACT software [2] designed to calculate the radionuclide compositions and radiation characteristics of SNF

and RW (alpha and beta particle yields, neutron and gamma radiation yields and spectra, energy release, activity, gas formation);
- improved graphic editor capabilities enabling the import of object models from a computer-aided design system (CAD), for example, Revit [3];
- development of modules providing the assessment of public exposure doses considering various types of water uses and particular types of biota;
- development of a module able to calculate permissible discharges of radioactive substances into surface water bodies.

This article discusses the state-of-art in the development of the KORIDA SP providing some examples of its application addressing relevant SNF and RW management problems.

Verification and validation of the TRACT code

The TRACT nuclide kinetics software is designed to model changes in the radionuclide composition and radiation characteristics of SNF and RW caused by the radioactive decay of unstable isotopes and nuclear reactions under neutron irradiation in the neutron energy range up to 20 MeV.

The TRACT SP was verified and validated based on a verification matrix (Table 1) with calculated and experimental data on the radionuclide composition, activity, decay heat of SNF from VVER-440, -1000, -1200 reactors and gamma radiation yield from metal materials irradiated in the BR-10 reactor.

Calculations implemented for test the problems from the verification matrix and their results were previously published in [10]—[12]. Figure 1 provides an example of software validation presenting a comparison between the mass contents of actinides and fission products in a fuel sample taken from VVER-440 SFAs with a burnup of 31.9 GW day/tU$_{ref}$ taken as a *calculation/experiment* ratio [8], [12].

Calculated and experimental data were compared. The results showed that generally a model could adequately represent the considered physical processes; for most isotopes, the calculation/experiment ratios were found to be ranging from 0.69 to 1.21. The revealed deviations of the results obtained were associated with measurement errors, uncertainties in the initial data involved in the calculations, as well as with errors in nuclear data on minor actinides. Further development of the software provides for the implementation of

Table 1. TRACT Verification Matrix

Purpose of the experiment/ calculation study	Irradiation source	Material
To calculate the activity and α-, β-, γ- energy release [4]	VVER-440 reactor (29.5 GW·day/tU)	Uranium dioxide with an enrichment level of 3.6 %
	VVER-1000 reactor (40.5 GW·day/tU)	Uranium dioxide with an enrichment level of 4.4 %
To calculate residual heat release (RB-093-20) [5]	VVER-440 reactor (30 GW·day/tU)	Uranium dioxide with an enrichment level of 3.6–4.87 %
	VVER-1000 reactor (40 GW·day/tU)	Uranium dioxide with an enrichment level of 3–4.95 %
	VVER-1200 reactor (50 GW·day/tU)	Uranium dioxide with an enrichment level of 3–4.95 %
To measure the residual heat release from decay products [6]	Reactor (thermal neutrons)	^{239}Pu, ^{233}U, ^{235}U
To measure γ-exposure from irradiated samples [7]	Reactor BR-10	V, V-Ti, V-Ti-Cr, V-Fe, Nb, Mo, Re, W
To measure mass concentrations of actinides and decay products	VVER-440 reactor	Uranium dioxide with an enrichment level of 3.6 %
	VVER-1000 reactor	Uranium dioxide with an enrichment level of 3.6 % and 4.4 %

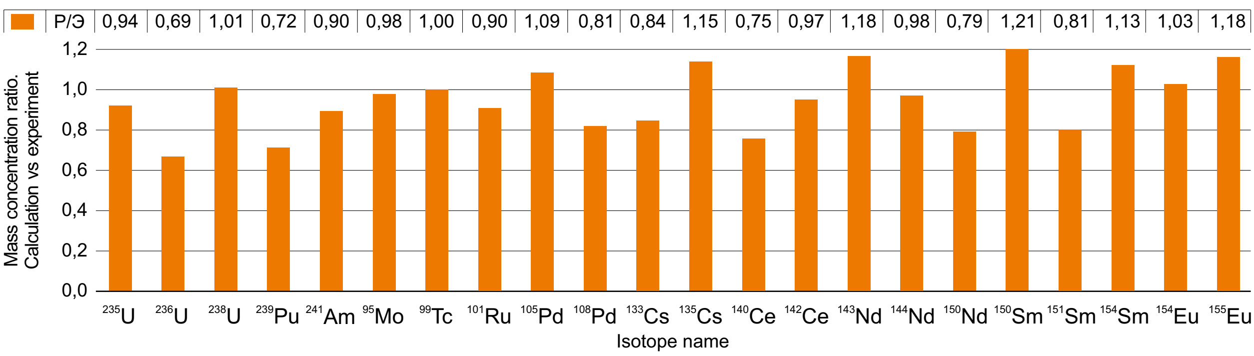

Figure 1. Breakdown for the mass contents of actinides and fission products in a sample at a fuel burnup of 31.9 GW day/tU$_{ref}$

algorithms that would assess the impact of initial data uncertainties on the calculation results.

TRACT software verification and validation was completed in 2021, a report was prepared with a set of documents formed to apply for a software certificate as part of the KORIDA SP.

Graphic editor development

Another important feature of the KORIDA SP is that it also involves the GRATOR graphic editor [13]: three-dimensional graphic models of objects can be developed in it with the primary information (about geometry, radiation sources, materials) converted into source data format that can be used in the calculation modules.

This editor is designed to import models of objects in a step format created in CAD as a set of solid primitives, edit them, create new graphic models, convert data on geometry, materials and radiation sources into source data file format for the TDMCC software [14], visualize calculation results combining them with the graphical model. The new version of the editor has an additional feature: geometric parameters of fragments can be imported from a digital information model of an object build in the Revit environment based on the laser scanning data.

Industrial facilities scanned using modern laser tools may provide effective and accurate data on their geometry (overall dimensions, orientation, position data). This method is of particular importance when it comes to the inspection of nuclear facilities being at the final stages of their life cycle, when the actual state of a facility may differ significantly from its original designs and the inspection time is limited due to the impact provided by the radiation background on the inspection personnel.

Primary laser scanning (LS) data (for example, premises with equipment) in the form of a point cloud (Figure 2a) are digitized using purpose-developed software in the Revit environment (Figure 2b, stage 1). This model is supplemented with the characteristics of materials and radiation sources (radionuclide composition and geometric parameters) and exported to the IFC file format. Thanks to the new features of the GRATOR editor one can import such a model, including all the specified characteristics (Figure 2c). In the future, the user has the opportunity of customizing the model given a specific task in the radiation safety assessment, generate a calculation model in the TDMCC software format and perform the calculation.

When the feasibility of decommissioning designs is evaluated, one should calculate the potential exposure doses to personnel given the proposed dismantlement options. Spatial distributions for the effective (equivalent) dose rate (EDR) of radiation can be calculated in KORIDA for each dismantlement stage, as well as personnel exposure dose considering the scenario of its spread. Presented below is a case study involving numerical model development for a fragment of a facility involving an installation designed for the chemical reprocessing of spent nuclear fuel. It provides some insights on how this problem can be solved using available PC tools.

Equipment in the premises of this facility is decontaminated and dismantled in accordance with the decommissioning designs, which is followed by equipment fragmentation and packaging of the generated waste into recyclable containers. The designs, in particular, provide for the removal of chemical processing unit from concrete canyons and shipment of large-sized equipment to the fragmentation site. Before the decommissioning operations start, one should assess personnel exposure at all stages of this process, therefore, the radiation situation in the vicinity of radioactively contaminated devices should be forecasted.

Computational models of the canyon with the unit were built in GRATOR editor before and after the upper slab was dismantled, as well as a model of

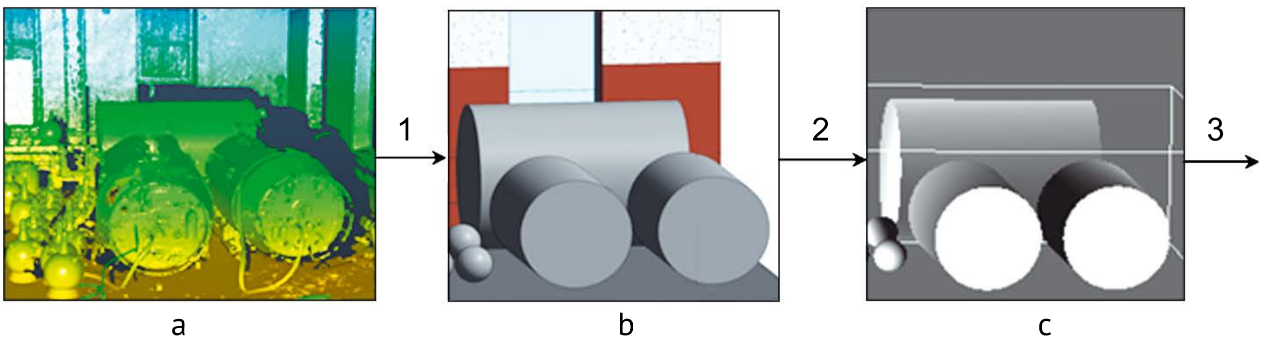

Figure 2. Types of models representing a premise with equipment at the first and second stages of their transformation: a) point cloud from LS; b) digitized model in the Revit environment; c) model in the GRATOR environment; 3 — stage of conversion into the calculation model

the removed unit in the assembly hall. The specific activities of the main dose-contributing isotope ^{137}Cs (^{137m}Ba) on the surface of the canyon and on the outer surface of the device were set based on the comprehensive engineering and radiation survey of the facility (KIRO). Figure 3 presents graphical model with different sections of the unit in the canyon and the calculated EDR field above it after the top slab was dismantled.

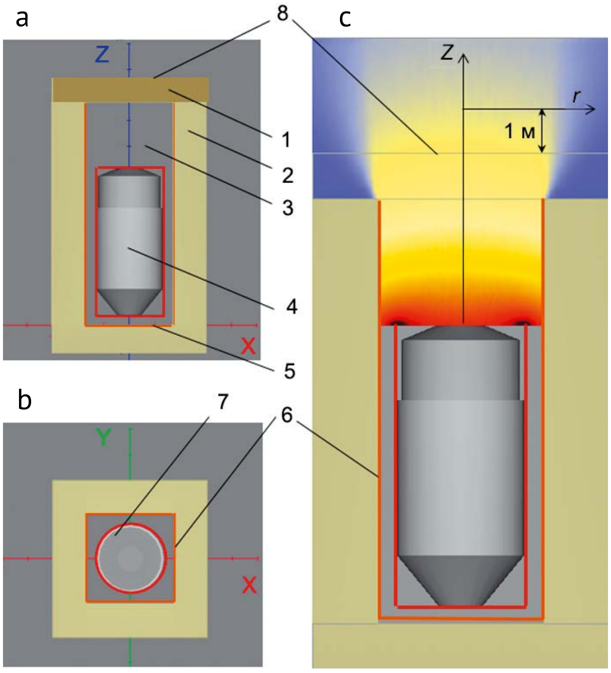

Figure 3. Longitudinal (a) and transverse (b) sections of a computational model representing a unit in a concrete canyon: 1 – upper slab; 2 – canyon walls; 3 – air; 4 – unit; 5, 6 – models of surface radiation sources at the bottom and walls of the canyon, 7 – model of a surface cylindrical radiation source, 8 – upper level of the floor slab; c – image of the EDR field above the unit without top cover

Spatial EDR distributions near the devices calculated in the KORIDA software were considered sufficient to predict the radiation situation in the premises at all dismantlement stages.

One should note that such calculations are often complicated by the insufficiency of the KIRO results (and/or their unsatisfactory accuracy) potentially causing some significant errors, for example, when the calculation results are normalized to the power of the radiation sources. To improve the quality of the KIRO survey, one should set relevant requirements for its implementation. Therefore, a computational and analytical approach is developed based on option-based EDR field calculations and solution of an inverse problem (recovery of source activity at constant EDR levels). This approach and its testing results were summarized in [15].

Ecorad family modules

Three new modules have been included into the KORIDA SP: Ecorad-DS, Ecorad-Aqua and Ecorad-Biota.

The Ecorad-DS module is designed to calculate allowable discharges of radioactive substances into surface water bodies during normal operation of nuclear facilities. The calculations are based on the Standards for Radioactive Substance Discharges into Water Bodies Acceptable for Water Users. Development Methodology [16] and on safety guidelines in the field of atomic energy use, namely, RB-126-17 [17] and RB-126-21 [18].

The Ecorad-Aqua module is designed to assess population exposure considering potential impact of the radiation factor in radiation safety assessments of nuclear facilities, including the long-term safety for RW disposal facilities. This module is used to evaluate scenarios of current and retrospective radiation contamination based on the monitoring data showing radionuclide concentrations in the aquatic environment, as well as considering predictive scenarios evaluating radioactive releases into water bodies. In the implemented models, population exposure is forecasted assuming various exposure pathways (Figure 4):

- external exposure when an individual is subject to impacts in the water use zone (exposed to water, rides boats, rests at the beaches, walks around irrigated areas, water meadows);
- internal exposure due to the consumption of drinking water, fish, as well as vegetable, meat and dairy products produced in irrigated areas, as well as due to the inhalation intake of radionuclides.

Figure 5 exemplifies the program's capabilities based on the population exposure calculated under the long-term safety assessment of a near-surface RW disposal facility (NSDF). The model considers the option of RW disposal in bulk in the underground part of the facility (according to the considered scenario, this facility is going to become a NSDF in the future). The waste subject to disposal are crushed building materials: concrete, bricks and radioactively contaminated soil. As the initial conditions for mass transfer, the total activity of each considered radionuclide in the entire repository was taken equal to $1 \cdot 10^{10}$ Bq.

To perform dose assessment calculations, input data on radionuclide content in the groundwater were previously obtained based on geological transport modeling implemented in the GeRa code [19].

In the example, critical population group was assumed as the one engaged in farming activities in the intermediate vicinity of the NSDF, consuming food produced in the area and drinking water from

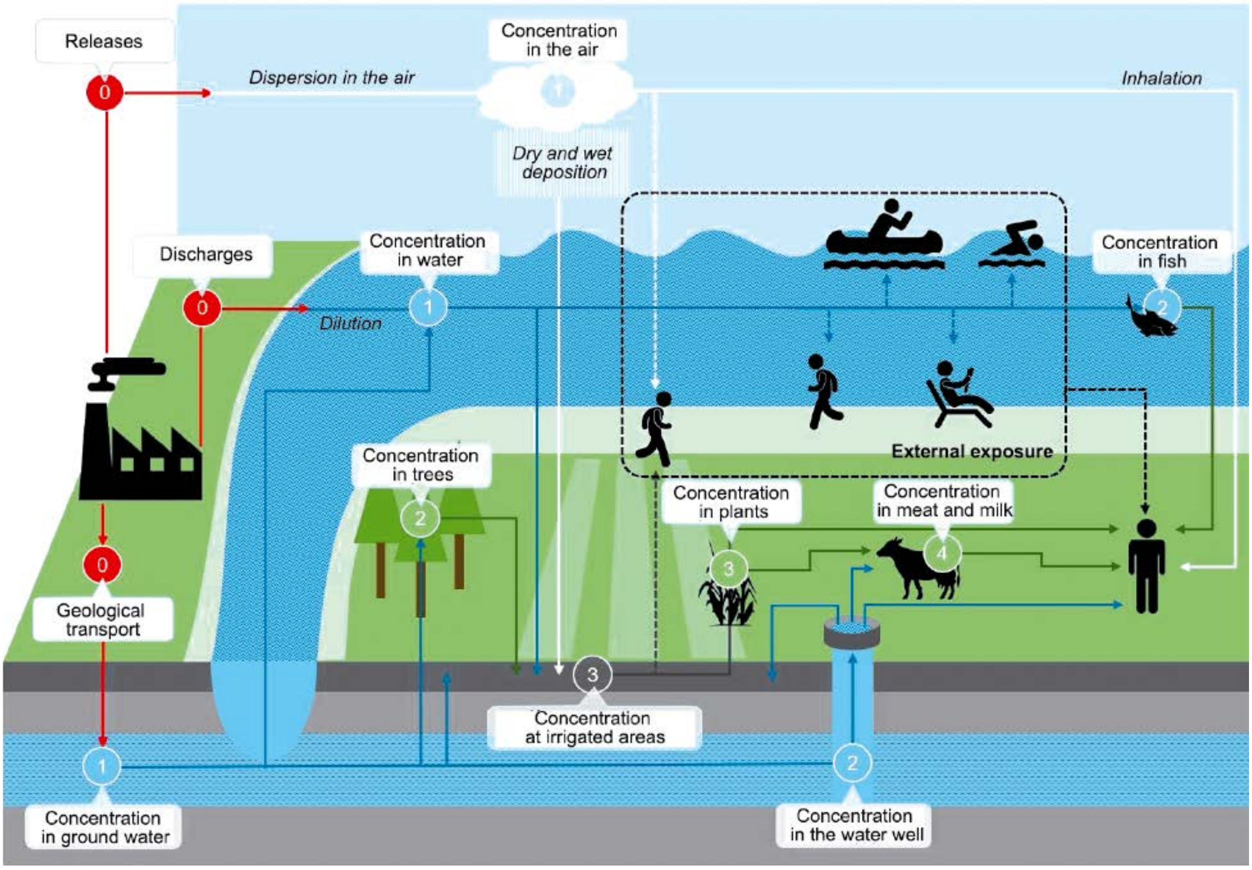

Figure 4. General layout showing the pathways of radionuclide transport in the environment and human exposure due to NF activities

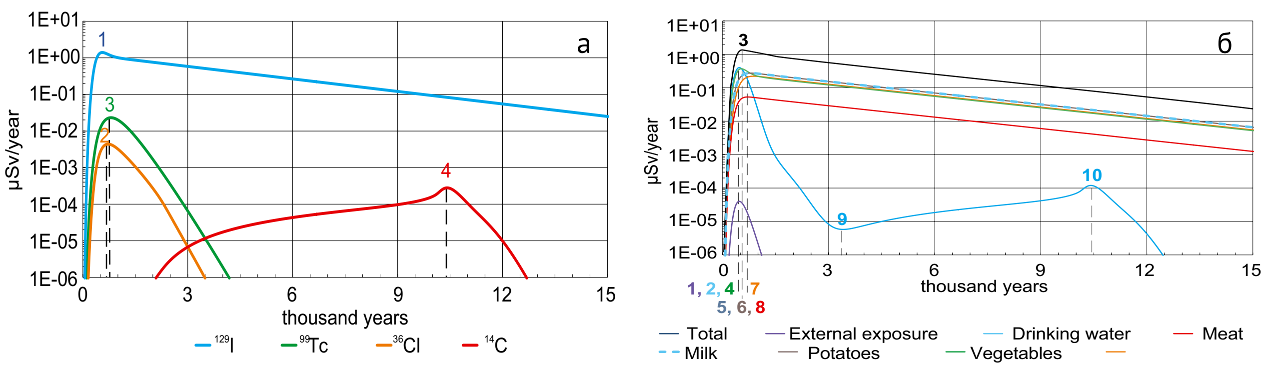

Figure 5. Example of a calculation performed in Ecorad-Aqua module focused on the exposure rate of a human during his lifetime

a) due to potential impact of different radionuclides in the NSDF (dotted line: maximum dose at the specific activity peak in the groundwater: 1 – ^{129}I, 2 – ^{36}Cl, 3 – ^{99}Tc, 4 – ^{14}C)

b) considering different exposure pathways (dotted line: the maximum dose at the time of peak activity in the groundwater: 1, 2, 4 – ^{129}I; 5, 6, 8 – ^{36}Cl; 7 – ^{99}Tc; 10 – ^{14}C, 9 – local minimum, when the specific activity of ^{14}C starts growing and when the specific activities of ^{36}Cl and ^{99}Tc start decreasing, 3 – absolute maximum of the radiation dose from all pathways)

local wells. As for the age groups, the adult group of population was selected.

The case study investigates a scenario assuming radionuclide release from RW into groundwater occurring after a standard-type NSDF is closed. It considers such a time period when the specific activity of radionuclides in water, namely, within the water use areas, reaches or overreaches its peak level and the content of radionuclides accumulated in the soil of irrigated agricultural lands reaches an equilibrium. At the same time, the spread of transuranic elements having much higher sorption capacities happens only within the near field of the repository.

The Ecorad-Biota module is designed to calculate radiation doses for those biota species that are considered characteristic for a given region based on the equilibrium contamination of the environmental components. The results obtained may be further used to calculate potential damage due to negative impacts produced on the biota [20], [21] or if the national standards for the use of natural resources are exceeded.

The Ecorad-Damage module is being developed to evaluate the economic damage: it implements a methodology developed by the Nuclear Safety Institute of RAS based on relevant Government Decrees of the Russian Federation and the Forestry Regulations of regions under consideration. After being appropriately tested, this module will be also integrated into the KORIDA SP.

Conclusion

This paper presents the results of the KORIDA SP development and some examples of its application aiming to address the following tasks:

- to calculate the radiation characteristics of SNF and RW under the test problems from the verification matrix of the TRACT software;
- to provide automated development of 3D calculation models representing radiation-hazardous facilities based on laser scanning data;
- to forecast the radiation situation at a nuclear facility seeking to minimize personnel exposure at the dismantlement stage.

Introduction of the Ecorad family modules enabled significant extension of the software capabilities as regards the assessment of potential ionizing radiation impacts on the population and biota.

Further development of the software package also provides for further upgrading of the graphical editor and the Ecorad family of modules, introduction of algorithms that would account for the errors in nuclear-physical data and assess the sensitivity of calculation results to the initial data uncertainty. A module is being developed to provide real-time dose rate assessment based on the formal description of accumulation factors. It is also thought to evaluate the errors in approximate calculations. The software package is being upgraded to a cross-platform interface.

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Information about the author

Arakelyan Aram Ajkovich, Research Associate, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: arakelyan@ibrae.ac.ru.

Blokhin Anatoly Ivanovich, PhD, Senior Researcher, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: bai@ibrae.ac.ru.

Blokhin Pavel Anatolievich, PhD, Head of laboratory, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: blokhin@ibrae.ac.ru.

Vaneev Yuri Evgenievich, Doctor of Science, Senior Researcher Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: yuvan@ibrae.ac.ru.

Kazieva Sabina Temergalievna, Junior Research Associate, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: kazieva@ibrae.ac.ru.

Kizub Polina Alexandrovna, Junior Research Associate, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: kizub@ibrae.ac.ru.

Kondakov Vasily Gavrilevich, PhD, Senior Researcher Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: kondakov@ibrae.ac.ru.

Panchenko Sergey Vladimirovich, Head of laboratory, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: panch@ibrae.ac.ru.

Sipachev Ivan Vasil'evich, Chief Specialist, Nuclear Safety Institute of the Russian Academy of Sciences (52, Bolshaya Tulskaya st., Moscow, 115191, Russia), e-mail: ivanushka1976@list.ru.

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Arakelyan A. A., Blohin A. I., Blohin P. A., Vaneev Yu. E., Kazieva S. T., Kizub P. A., Kondakov V. G., Panchenko S. V., Sipachev I. V. Refinement of KORIDA software complex and its application in addressing SNF and RW management problems. *Radioactive Waste,* 2022, no. 3 (20), pp. 107—116. DOI: 10.25283/2587-9707-2022-3-107-116. (In Russian).