Safety Assessment and Visualization Technology for Radiation Fields in Small Pressurized Water Reactors

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Abstract

Small reactors feature compact structures, complex refueling processes, and spent fuel with strong radioactivity; therefore, assessment of radiation doses during the refueling process is particularly important. This study conducted burnup calculations and dose calculations for spent fuel assemblies from KLT-40S (Korabl -Likhterovoz -Transportnii -40 MW Series, marine 40 MW improved reactor) after 1278 days of full-power operation, established a model of the floating nuclear power platform using the 3D modeling software 3Ds MAX, and achieved visualization of the spatial radiation dose field and refueling operation process through the virtual simulation engine Unity. The results indicate that when hoisting spent fuel assemblies within a shielding cask, the dose rate inside the geometry of the spent fuel assembly reaches a maximum level of 1.36×10^{4} Sv/h, while at a location 3 meters from the geometric center of the spent fuel assembly, the spatial radiation dose rate is 6.02 Sv/h. In the event of spent fuel assembly damage, according to the human radiation dose calculation model, the residence time for workers in the reactor compartment is approximately 14.60 h to 38.46 h. The spatial distribution of the magnitude of the radiation dose field becomes more intuitive with the support of visualization technology. The dose assessment for the refueling process, combining simulation analysis and visualization technology in this study, can provide support for design and analysis of refueling process technology for small reactors.

Full Text

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Abstract

The compact structure of small reactors, combined with the complexity of the refueling process and the high radioactivity of spent fuel, makes radiation dose assessment during refueling particularly critical. This study performed burnup and dose calculations for KLT-40S (Korabl-Likhterovoz-Transportnii-40 MW Series, a marine 40 MW improved reactor) spent fuel assemblies after 1278 days of full-power operation. A floating nuclear power platform model was constructed using 3Ds MAX software, and spatial radiation dose field visualization and refueling workflow visualization were implemented using the Unity virtual simulation engine. The results indicate that when lifting spent fuel assemblies within a shielding sleeve, the dose rate inside the assembly geometry reaches a maximum of 1.36$×10^{4}$ Sv/h, while at 3 meters from the assembly center, the spatial radiation dose rate is 6.02 Sv/h. In the event of spent fuel assembly breakage, based on the human radiation dose calculation model, the permissible residence time for workers in the reactor compartment is approximately 14.60 to 38.46 hours. Visualization technology provides a more intuitive representation of the spatial distribution of the radiation dose field. This integrated approach combining simulation analysis with visualization technology for dose assessment during the refueling process can support the design and analysis of refueling procedures for small reactors.

Keywords: Floating nuclear power plant; Loading and refueling; Radiation field; Visualization; Dose assessment

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Background

Small reactors feature compact structures and complex refueling processes, with spent fuel exhibiting strong radioactivity, making radiation dose assessment during refueling particularly crucial. For marine reactors, refueling is conducted at sea, necessitating consideration of factors such as high winds and waves, limited operating space, and increased risk of collision, thereby requiring more meticulous planning of the refueling process.

The purpose of this study is to evaluate the KLT-40S (Korabl-Likhterovoz-Transportnii-40 MW Series, Ship-mounted Loop-type Turbine-driven 40 MW Serial/Upgraded Reactor) spent fuel assemblies after 1278 Effective Full Power Days (EFPDs) of operation through burnup and dose calculations.

Unlike conventional nuclear power plants situated on stable land, floating nuclear power platforms (small modular pressurized water reactors) undergo refueling processes aboard vessels. Additionally, the power levels of floating nuclear power platforms differ from traditional nuclear plants. Therefore, modeling and calculations must be based on the actual design parameters of floating nuclear power platforms to complete the visualization of radiation field distribution during their loading and refueling processes. The KLT-40S (Korabl-Likhterovoz-Transportnii-40 MW Series, Marine 40 MW Improved Reactor) is a small modular reactor developed by Russia' s OKBM (Afrikantov Experimental Design Bureau for Mechanical Engineering) based on the KLT-40 reactor [1]. Russia has built the world' s first floating nuclear power platform, the *Akademik Lomonosov*, equipped with two KLT-40S reactors.

Internationally, Vadim Naumov et al. [2] studied the comparison of spent fuel radioactivity between KLT-40S and RITM-200M small reactors; Beliavskii et al. [3] simulated the effects of thorium-uranium fuel on fuel lifetime and burnup for the KLT-40S reactor using Monte Carlo methods. Given that few small reactors have been commercially operated to reach their designed burnup lifetime and undergo shutdown for refueling, and considering that marine reactor refueling occurs at sea with factors such as rough seas, confined operating spaces, and higher collision risks, careful planning of the refueling process is essential. Overall, the foundation for radiation dose assessment and visualization research on small reactor loading and refueling processes remains relatively weak [4-7].

Meanwhile, with the development of virtual reality and augmented reality engines, three-dimensional visualization technology can display more intuitive and comprehensive physical information [8-10] and is playing an increasingly important role in reactor refueling scheme design, optimization, and safety assessment [11-13]. Therefore, this study developed an Intelligent Evaluation and Planning Platform for Radiation Doses of Multi-functional Small Modular Reactors based on virtual simulation engines, depletion/activation programs, Monte Carlo programs, and path planning procedures. Using this platform, research was conducted on the visualization of the KLT-40S small modular reactor' s onboard loading and refueling process and personnel radiation dose assessment.

The research content is illustrated in [Figure 1: see original paper]. After the KLT-40S small reactor with a four-loop fuel assembly design completed 1278 EFPDs (Effective Full Power Days), radiation field dose assessment and process visualization for the reactor loading and refueling process were performed. First, the radiation dose safety assessment and scenario planning platform calls the ORIGEN2 depletion calculation program to perform activity calculations for the KLT-40S spent fuel assemblies, obtaining output files of radiation source intensity for the spent fuel assemblies and shielding materials. It then calls the Monte Carlo program Super MC to perform radiation field calculations, obtaining text files of spatial radiation field distribution results for the material exchange process, which serve as input for radiation field visualization rendering in the virtual scenario. Next, the path generation program generates staff walking paths based on spatial coordinate text data provided by the user. Finally, the platform implements dynamic changes in the radiation field during the KLT-40S reactor loading and refueling process based on the Unity 3D engine, as well as dynamic visualization of different radiation doses received by personnel during scene switching. For example, using spent fuel assembly breakage criterion analysis methods and the ICRP human irradiation dose assessment model, the platform analyzes radiation dose levels received by workers operating in real-time in a nuclear emergency scenario when radioactive noble gases fill the reactor compartment space due to breakage of spent fuel assemblies during the lifting process.

1.1 Burnup and Activation Calculation

ORIGEN2 is a depletion and activation calculation program developed by Oak Ridge National Laboratory. It employs a single-group cross-section approach with short computation times and can simulate various neutron-induced nuclear reactions with nuclides in nuclear fuel, calculating the accumulation and decay of radioactive materials during nuclear reactions. It provides source term parameters such as nuclide composition, radioactivity, and neutron and photon yields, making it suitable for burnup, activation, and decay calculations for different reactor types. The ORIGEN2 calculation model incorporates several assumptions: first, neutron flux and reaction cross-sections are assumed not to vary with nuclide composition; second, all nuclides are assumed to occupy the same spatial point and undergo equal neutron irradiation, thus it cannot handle geometry-related issues such as spatial distributions of neutron flux density and dose rates [14-15]. Based on reactor burnup cycle, power density, and nuclear fuel composition information, the ORIGEN2 program can calculate the radioactivity of spent fuel, serving as the input source intensity coefficient for Monte Carlo dose calculations.

Generally, the rate of change in the number of nuclide i over time, dN/dt, can be expressed by the following non-homogeneous first-order ordinary differential equation:

$$\frac{dN_i}{dt} = \sum_{j\neq i} \lambda_j f_{ij} N_j + \phi \sum_{k\neq i} \sigma_k f_{ik} N_k - (\lambda_i + \phi\sigma_i + R_i) N_i + S_i$$

In equation (1): N is the atomic density of nuclide i; λ is the decay constant of nuclide j; f is the fraction of nuclide j decaying to i; ϕ is the average neutron flux; σ is the average neutron absorption cross-section of nuclide k; f is the fraction of nuclide k reacting with neutrons to generate i; R is the continuous removal rate of nuclide i from the system; and S is the continuous supply rate of nuclide i to the system.

1.2 Radiation Field Calculation

This study uses the Super MC3.3 program to calculate the spatial radiation dose of spent fuel assemblies during the refueling process. The Institute of Nuclear Energy Safety Technology of the Chinese Academy of Sciences began independent development of the Super Monte Carlo Core Computational Simulation Software System (Super MC) in 1999 [16]. Super MC3.3 supports transport simulation of various particles including neutrons (1 e^{-11} to 150 MeV), photons (1 keV to 1 GeV), electrons, and protons. It can calculate and tally commonly used physical quantities in nuclear design and analysis, as well as novel reactor physics parameters such as k. The flux estimation based on the track length method is [17]:

$$\phi = \frac{1}{V}\sum_{i\in T} l_i w_i$$

where T represents all particle track sequences in the volume of interest, l is the length of track i, and w is the sum of particle weights.

Reaction rate calculations are generally based on flux estimation, and the track length estimate of reaction rates can also be obtained by multiplying equation (2) by the microscopic cross-section:

$$R = \phi\sigma = \frac{1}{V}\sum_{i\in T} l_i w_i \sigma$$

The power density at any point r in the core, i.e., the power per unit volume at r, is:

$$q'''(r) = \Sigma_f \phi(r) E_f$$

where Σf is the macroscopic fission cross-section of fissile material, $\phi(r)$ is the neutron flux density at r, and Ef is the energy released per fission.

1.3 Voxel Model

When considering spent fuel assembly breakage, external irradiation from environmental sources of radioactive nuclides is an important pathway for radiation exposure to workers engaged in nuclear facility maintenance, originating from routine emissions, major accident releases, or environmental contamination following radioactive material leaks. The International Commission on Radiological Protection (ICRP) comprehensively evaluated age-dependent internal irradiation dose coefficients in Reports 56, 67, 69, 71, and 72 (ICRP, 1990, 1993, 1995a,c,d), and published updates to adult reference dose coefficients in the *Occupational Intakes of Radionuclides* series (ICRP, 2015, 2016a,b, 2017a, 2019). ICRP Publication 144 provides age-dependent external environmental exposure dose rate reference coefficients for the public [18]. When dose rate coefficients are needed to evaluate measurements or assessments of environmental radioactivity concentrations, air radiation rates, air absorbed dose rates, or ambient dose equivalent rates, calculating dose coefficients requires assessment of the environmental field (e.g., irradiation source geometry, soil density and composition, distribution of radionuclide concentrations in environmental media), radiation information, and human computational models (representing reference voxel models of the exposed public), as shown in [Figure 2: see original paper], as well as transport simulation of radiation in environmental media and the anatomical structures of exposed individuals.

1.4 Three-Dimensional Modeling and Radiation Field Rendering

In the platform, the visualization process requires simulation of three stages: (1) establishment of the three-dimensional scene, including the floating platform model and marine environment; (2) dynamic processes of KLT-40S reactor refueling and fuel loading; and (3) spatial radiation field visualization and human dose assessment.

Three-dimensional modeling software is used to construct the three-dimensional model of the *Akademik Lomonosov* floating nuclear power platform. The *Lomonosov* hull has numerous components with complex structures, requiring powerful solid design modeling software. 3Ds MAX is a three-dimensional model creation and rendering software developed by Autodesk, widely used in various design fields due to its good interactive extensibility, rich plugins, and powerful modeling functions. Spatial radiation field rendering is implemented using volume rendering technology, which converts three-dimensional radiation field volume data into color values and opacity using mapping functions, composes them into three-dimensional textures in a specific order, creates materials using the three-dimensional textures, generates solids using slice meshes, binds the solids to scene nodes, and finally binds the materials to the solids for volume rendering.

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2 System Composition and Architecture

The computational platform used in this study employs the virtual simulation engine tool Unity 3D to construct a virtual reality scenario of the KLT-40S refueling process. Unity 3D, as an important virtual reality development platform, provides functions for data interaction, integrated simulation, visualization, and application programming interfaces. The radiation field rendering process in Unity is shown in [Figure 3: see original paper]. Virtual reality development engines cannot directly use mesh models constructed by mainstream CAD (Computer Aided Design) modeling software and require conversion of three-dimensional models to mesh models. This study uses the FBX format file, specifically by exporting three-dimensional models created in 3Ds MAX software (version 3Ds MAX 2022) through the software' s export function to the universal FBX format for Unity 3D (version 2022.3.17f1c1), where dose radiation field visualization rendering and loading/refueling process visualization are performed.

As shown in [Figure 4: see original paper], the overall visualization process consists of four parts: floating platform scene construction, real-time radiation dose display, loading/refueling process confirmation, and personnel dose assessment. By integrating these processes into the Unity engine, visualization research on the reactor refueling process is completed. Since the Unity engine can read multiple scene files, this radiation dose safety assessment and scenario planning platform can quickly call up actual application scenarios according to different operational requirements for spatial radiation dose assessment. Meanwhile, due to the compact and complex equipment arrangement within the ship, paths automatically generated using the shortest path method may pass directly through equipment, which is unrealistic. Therefore, based on user-preset three-dimensional spatial paths, personnel radiation dose assessment under specific radiation fields is completed. Physical quantities such as total path length, maximum radiation dose rate along the path, and cumulative dose are displayed in real-time on the platform' s UI interactive interface. By comparing final results, rapid generation of personnel minimum radiation dose schemes under different path options is achieved.

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3 Numerical Model Calculation

3.1 KLT-40S Reactor Parameters According to literature [19], the *Akademik Lomonosov* began operation in May 2020, with two KLT-40S reactors installed on board. The first reactor began refueling preparation in November 2023, with refueling completed in December 2023. Therefore, its burnup cycle is 3.5 years, consistent with the original design refueling cycle of 3–4 years. Table 1 presents the main design parameters of the reactor on the floating platform.

Table 1 KLT-40S Reactor Design Parameters

Parameters	Values	Parameters	Values
Thermal power / MW	⟦value⟧	Number of fuel assemblies	⟦value⟧
Fuel assembly across flats size / mm	⟦value⟧	Triangular lattice pitch / mm	⟦value⟧
Core height / mm	⟦value⟧	Average uranium enrichment	14.1%
Uranium-235 inventory /	⟦value⟧	Uranium inventory / kg	⟦value⟧
Core diameter / mm	⟦value⟧	Number of fuel elements in fuel assembly	⟦value⟧

3.2 Radiation Calculation Based on the burnup cycle in Section 3.1, the ideal burnup depth for the first KLT-40S reactor is 150 MW × 1278 days = 1.917×10^{5} MWD. The shutdown decay time is one month.

Table 2 Activity of the Main Nuclides in the Spent Fuel of the Whole Reactor (Bq)

Nuclide	Activity	Nuclide	Activity
^{103}Ru	1.78×10^{15}	^{106}Ru	4.36×10^{16}
^{103} Rh	3.68×10^{16}	^{106}Rh	5.58×10^{16}
^{125}Sb	1.50×10^{16}	^{129}Te	4.36×10^{16}
^{129} Te	1.50×10^{16}	^{133}Xe	1.48×10^{15}
^{134}Cs	5.05×10^{16}	^{136}Cs	1.13×10^{15}
^{137}Cs	7.16×10^{16}	^{137} Ba	1.74×10^{15}
^{140}Ba	9.20×10^{16}	^{140}La	5.64×10^{16}
^{141}Ce	3.77×10^{16}	^{143}Pr	1.40×10^{15}
^{144}Ce	1.84×10^{16}	^{144}Pr	1.74×10^{16}
^{144} Pr	2.10×10^{16}	^{147}Nd	2.41×10^{16}
^{147}Pm	5.32×10^{16}	^{154}Eu	2.24×10^{16}
^{155}Eu	1.17×10^{17}	^{156}Eu	1.17×10^{17}

According to literature [1], the reactor compartment space is a rectangular volume of 12 m × 7.92 m × 12 m. ORIGEN2 calculations show that 30 days after KLT-40S shutdown, the total photon source intensity of the entire core’ s spent fuel assemblies is 9.18×10^{17} photons/second. With 121 assemblies in the reactor, the photon source intensity per spent fuel assembly is 7.59×10^{15}, which serves as the source intensity coefficient for Super MC dose calculations.

For the spatial radiation field, the reactor compartment space was divided into 10 cm × 10 cm × 10 cm spatial grids using the mesh tally method, resulting in $120 \times 80 \times 120 = 1{,}152{,}000$ calculation points for the spatial radiation field distribution, with 10^8 particles simulated.

[Figure 5: see original paper] and [Figure 6: see original paper] show the spatial radiation field at different heights (along the Y-axis) during the spent fuel assembly lifting process. The left side shows the XZ plane view at Y = 0 m, while the right side shows the XZ plane view at Y = 8 m. According to the calculations, the spatial radiation dose rate decreases radially outward from the center of the spent fuel. The dose rate inside the spent fuel assembly geometry reaches a maximum of 1.36×10^{4} Sv/h. At 3 meters from the assembly center, the spatial radiation dose rate is 6.02 Sv/h, and at 6 meters from the center, it is 1.16 Sv/h.

3.3 Visualization Implementation [Figure 7: see original paper] shows the rendering effect of the *Lomonosov* geometric model by the seaside. By modeling the main floating platform body and internal compartments and equipment, interaction between the radiation field and refueling scenarios is achieved.

During the refueling operation, the crane hook lifts the spent fuel assembly from the core through a 1 cm-thick lead shielding sleeve.

[Figure 8: see original paper]–[Figure 11: see original paper] illustrate the dynamic refueling process in Unity. [Figure 8: see original paper] shows the platform opening the reactor cover after shutdown. This unloading adopts a scheme of lifting individual assemblies one by one, as shown in [Figure 9: see original paper]. As the spent fuel assembly displaces spatially, the radiation field changes dynamically. After unloading from the core, spent fuel assemblies are transported to the adjacent spent fuel storage room, which contains empty storage boxes. All spent fuel assemblies are sequentially transferred into the storage boxes, which are then sealed and left to stand after unloading completion, as simulated in [Figure 10: see original paper]. [Figure 11: see original paper] demonstrates the core loading process, where new fuel is loaded into the core container from the new fuel room adjacent to the reactor compartment. Since new fuel has not undergone fission reactions and does not possess high radioactivity, radiation field changes during the loading process are not simulated.

3.4 Accident and Personnel Dose Assessment Noble gases are chemically stable, not easily depleted, and migrate with gas diffusion at a migration speed positively correlated with temperature. Compared with other fission products, when fuel rods in spent fuel assemblies rupture, fission gases ^{85}Kr and ^{133}Xe are most likely to be released into the entire reactor compartment space.

From Table 2, the activity of ^{85}Kr in the core spent fuel assemblies after shutdown is $A_{85} = 1.78\times10^{15}$ Bq, and that of ^{133}Xe is $A_{133} = 2.89\times10^{15}$ Bq. Therefore, the activity of ^{85}Kr in a single fuel rod is $A_1 = 2.13\times10^{11}$ Bq, and that of ^{133}Xe is $A_2 = 3.46\times10^{11}$ Bq. The reactor compartment volume is approximately $V = 1140.48$ m^3.

Breakage criterion analysis employs the minimum probability method with the following assumptions [20]: (1) Only one fuel rod is broken among the 121 spent fuel assemblies (totaling 8349 fuel rods), with a breakage probability $f_1 = 1.198\times10^{-4}$. (2) Considering the pressure inside the cladding is higher than in the reactor compartment space, i
$f_2 = 1$.

The specific activity of released ^{85}Kr and ^{133}Xe can be calculated using the following formula:

$$C = \frac{A}{V} = \frac{N \cdot A_{rod}}{V}$$

where C is specific activity (Bq/m^3), N is the total number of fuel rods, and V is the containment volume (m^3). With K as the specific activity coefficient, formula (5) becomes:

$$C = K \cdot \frac{N}{V}$$

According to ICRP Publication 144, the air conversion dose coefficients for adult males in a radiation environment are 7.78×10^{-4} nSv/h/Bq/m^3 for ^{85}Kr and 4.03×10^{-3} nSv/h/Bq/m^3 for ^{133}Xe.

Table 3 Air Conversion Dose Factors

Nuclide	Specific Activity K, coefficient of specific activity	Air environment cumulative effective conversion factor / mSv/h/Bq/m^3	Human dose from radiation exposure / mSv/h
^{85}Kr	2.13×10^{11}	8.77×10^{-4}	7.78×10^{-10}
^{133}Xe	3.46×10^{11}	8.77×10^{-4}	4.03×10^{-9}
Total			

To simulate exposure to environmental radiation fields, ICRP Publication 144 discusses three typical environmental source cases: (1) soil (ground) contamination simulated as an infinite plane source at and below the surface; (2) air immersion simulated as a semi-infinite volume source of radionuclides in air; and (3) water immersion simulated as an infinite volume source of radionuclides in water. Considering the specific source geometry, for ground contamination the source size is considered infinite while the irradiation geometry space is considered semi-infinite, allowing selection of either an "infinite plane source on the ground" or a "horizontal infinite plane source" calculation model. During air immersion, the body is irradiated by an infinite air source from the ground, making the geometry space "semi-infinite."

[Figure 12: see original paper] shows the scenario where noble gases diffuse throughout the reactor compartment when a spent fuel assembly breaks. According to calculations, when radioactive noble gases fill the entire compartment, maintenance personnel must consider the air immersion coefficient when entering. For adult males, as shown in [Figure 12: see original paper], with the radiation source centered on the broken spent fuel assembly, the maximum radiation dose rate to the human body is 1.37 mSv/h, while the dose rate in the corners of the reactor compartment is approximately 0.52 mSv/h.

[Figure 13: see original paper] displays real-time maximum dose rates along the path and cumulative radiation dose levels for personnel under different scenarios and path options. According to this assessment model, the annual average individual dose for radiation workers should be less than 20 mSv [21]. In the event of such a radiation leakage accident, the permissible residence time for maintenance personnel in the reactor compartment is approximately 14.60 to 38.46 hours.

This study evaluated the radioactivity of spent fuel assemblies and calculated the spatial radiation dose field distribution for the KLT-40S reactor loading and refueling process. An intelligent evaluation and planning platform for radiation doses of small modular reactors was developed based on the Unity 3D virtual simulation engine, enabling dynamic visualization of the above processes and completing dynamic interaction between the spatial radiation dose field and the virtual simulation scenario of the floating nuclear power platform. Finally, based on fuel rod breakage criterion analysis methods, the impact of radiation doses on maintenance personnel was assessed for collision accidents during spent fuel assembly lifting that result in cladding breach.

Author Contributions

Wu Jiebo was responsible for simulation calculations, data compilation, and drafting the initial manuscript; Shi Jiangwu and Liu Guangkun conducted literature research and compilation; Bi Yuepeng and Wei Wei performed data processing; Zhao Yanan revised the manuscript; Xia Genglei provided technical guidance; Zhu Haishan secured research funding and finalized the manuscript.

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Note: Figure translations are in progress. See original paper for figures.