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Short Communication

A brief investigation of the dose field virtual simulation tools for reactor decommissioning and preliminary design for the HWRR reactor in China

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Abstract

The calculation and visualization of the dose field in the decommissioning of nuclear facilities is one of the important functions of the decommissioning virtual simulation system. The dose field simulation tools can provide radiation field distribution and play an important role in determining the decommissioning plan and protecting personnel during the engineering implementation process. This article investigates the development of dose field calculation and visualization in the reactor decommissioning virtual simulation systems. A preliminary technology plan suitable for the development of the decommissioning dose field calculation and visualization display programs of the first Heavy Water Research Reactor (HWRR) in China is proposed. The applicability of the selected scheme is analyzed. The functional requirement and development direction of the HWRR reactor decommissioning dose field tool are preliminarily determined. Furthermore, the reactor vessel of HWRR reactor is modeled, the dose field distribution is calculated and visualized based on the preliminary decommissioning code. This research can provide technical support for the development of the decommissioning simulation system for the first HWRR reactor in China.

Keywords

HWRR reactor, Decommissioning, Dose field calculation, Visualization

1. Introduction

The decommissioning of nuclear reactor is a measure need to be taken when the reactor is permanently shut down, with the purpose of permanently and explicitly improving its condition to meet the safety protection requirements. The decommissioning of nuclear facilities has become an important issue in the world nuclear industry. In the Level 3 decommissioning defined by the IAEA, it is required to remove all radioactive components and dismantled materials, so that the radiation levels in the plant are at or near the environmental background. However, the cost is very expensive. At present, countries around the world have placed a special emphasis on developing suitable methods and approaches for decommissioning processes. Therefore, it is necessary to conduct pre-analysis and simulation for the possible decommissioning projects (Zheng et al. 2007). The dose field virtual simulation system can become a powerful auxiliary tool for the decommissioning engineering, providing a support platform for the determination of decommissioning plans, the process planning and optimization, personnel training etc (Liu et al. 2011). It can present accurate and intuitive radiation field distribution during the design of reactor decommissioning schemes, and plays an important role in personnel protection during the engineering implementation process (Zhang et al. 2018).

The Heavy Water Research Reactor labeled 101 is the first research nuclear reactor in China, which was built in 1956. HWRR was put into operation from June 1958 to December 2007. It has been operating for nearly 50 years and has made historic contribution to the development of nuclear science and technology in China. The transition period from 2008 to 2013 was the final safe shutdown stage, and preparations for decommissioning were officially carried out. At present, the first phase decommissioning of the HWRR reactor has been approved (Ding et al. 2012; Zhang et al. 2016; Sun et al. 2018; Wu et al. 2020; Li et al. 2021a; Li et al. 2021b; Ren et al. 2022; Ren et al. 2023), related work has been carried out gradually, involving the dismantling of peripheral equipment, pipelines, etc.

This article conducts the progress on the development of dose field calculation and visualization tools for the reactor decommissioning. A preliminary technology solution for the dose field calculation and visualization program suitable for HWRR reactors is proposed. The outer shell of the HWRR reactor is modeled, the distribution and visualization of the dose field are calculated to test the tool preliminarily.

The content of this paper is organized as follows. The progress of the dose field virtual simulation system for reactor decommissioning is presented in Section 2. Section 3 is the introduction about the technical scheme suitable for the development of dose field calculation and visualization tool of HWRR reactor decommissioning. The final conclusion is provided in Section 4.

2. Dose field virtual simulation system for reactor decommissioning

The research on the application of does field virtual simulation technology for the reactor decommissioning in foreign countries started early and has made important contributions to the economy of decommissioning plans. Studying the decommissioning technology of nuclear facilities through virtual simulation technology, verifying the feasibility of technical solutions, and optimizing the decommissioning process have become an important direction in nuclear facilities decommissioning.

Since the 1980s, the French Atomic Energy Commission (CEA) has developed multiple simulation programs, including MERCURAD (Suteau et al. 2004; Abou 2010), CHAVIR (Leservot and Chodorge 2005; Thevenon et al. 2006), and NARVEOS (Thevenon et al. 2009; Thevenon 2011). MERCURAD is a three-dimensional dose field simulation program that uses the point kernel method (PKM) to calculate dose rates. PKM is a traditional method to estimate the radiation dose level and is widely utilized in radiation rate calculations. Point-kernel method is macroscopic approach used for radiation rate calculations. In PKM, radiation source volume is divided into elementary cells named point kernels. Each point kernel gives contribution to the radiation rate at the detecting point. PKM offers the advantage of rapid calculation for deep penetration problems, so the PKM is the primary way to achieve real-time 3D radiation field simulation (Prokhorets et al. 2007; Zhang et al. 2021). As for MERCURAD, several function modules such as shielding material library, cumulative factor calculation, energy group division, dose point definition, dose field calculation and printing calculation reports etc are established. When calculating the dose fields, multiple layers of different shielding materials can be selected. The total cumulative factor of shielding for different materials can be calculated, the dose field calculation grid can be defined. Furthermore, the calculation of the dose field and the output of the dose field calculation results can be obtained. The typical presentation for MERCURAD code can be seen in Fig. 1 (Suteau et al. 2004).

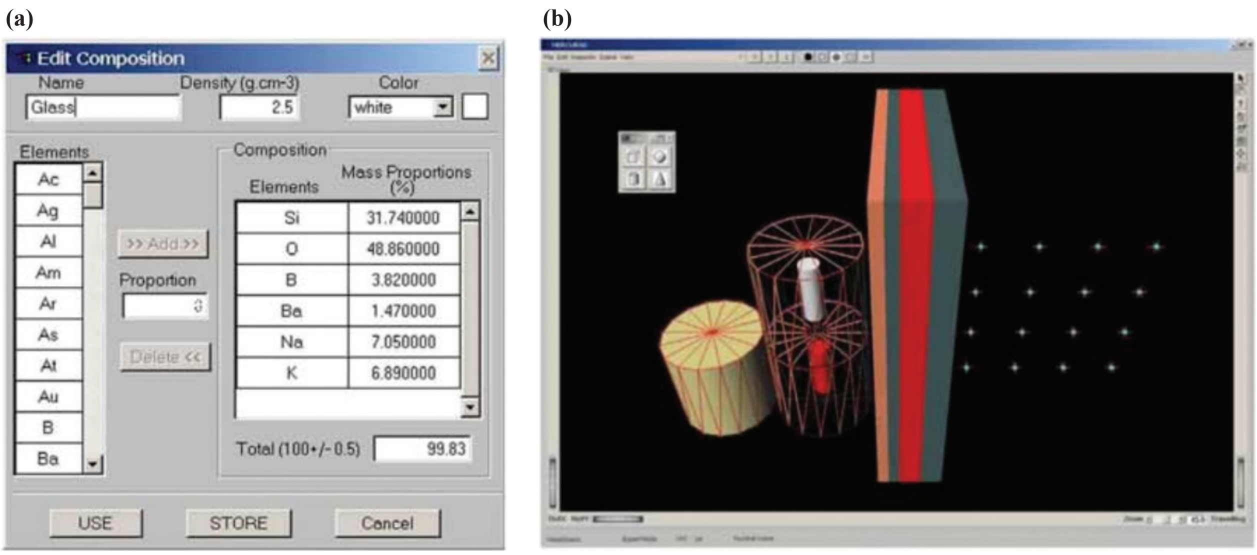


Figure 1. (a) Selection of multilayer shielding materials in MERCURAD code; **(b)** Visualization display in MERCURAD code.

CHAVIR is a software used for nuclear facility maintenance and decommissioning, which can realize scene setting and fast calculation of radiation exposure (Leservot and Chodorge 2005; Thevenon et al. 2006). The scenario definition function of this software is established by the Dassault software package VIRTOOLS. The dose calculation function is partially implemented using the algorithm and function modules in the MERCURE code package, such as material selection, cumulative factor calculation, energy group division, etc. The CAD model of CHAVIR software can be established from the predefined basic objects within the software, or can be imported from other CAD codes. CHAVIR software can calculate the radiation exposure of point source and body source. The point source uses the point kernel method to calculate the radiation exposure, and the body source uses the Monte Carlo method to calculate the radiation exposure by gridding the body source. The coupling calculation of the two methods also can be used to simulate the dose field. This software can define measurement points in the scene, and then calculate the dose rate of each measurement point. At the same time, CHAVIR can achieve dynamic calculation of the dose field and staff exposure dose, which can guide the dismantling of retired facilities. Fig. 2 shows the visualization model of nuclear power plants and equipment room in CHAVIR.

NARVEOS is a software system that combines the virtual reality technology and point kernel method to calculate dose field (Thevenon et al. 2009; Thevenon 2011). The software supports retirement scenario design and rapid dose calculation, which based on the principle of radiation assessment optimization (ALARA) to estimate the dose rates. This software can import 3DXML format files from CAD and use Dassault's 3DVia XM player to achieve virtual simulation of retirement scenarios, so that the operating environment of personnel in dose scenarios can be visualized. Fig. 3 shows the exposure dose in personnel operation paths. And the NARVEOS can also provide optimization suggestions for personnel protection to reduce exposure dose.

Électricité de France developed PANTHERE software (Longeot et al. 2014), which uses the point kernel method to calculate the radiation exposure rate of complex source terms and a large number of observation points in the three-dimensional scene. Moreover, PANTHERE can build custom geometry and import other CAD models.

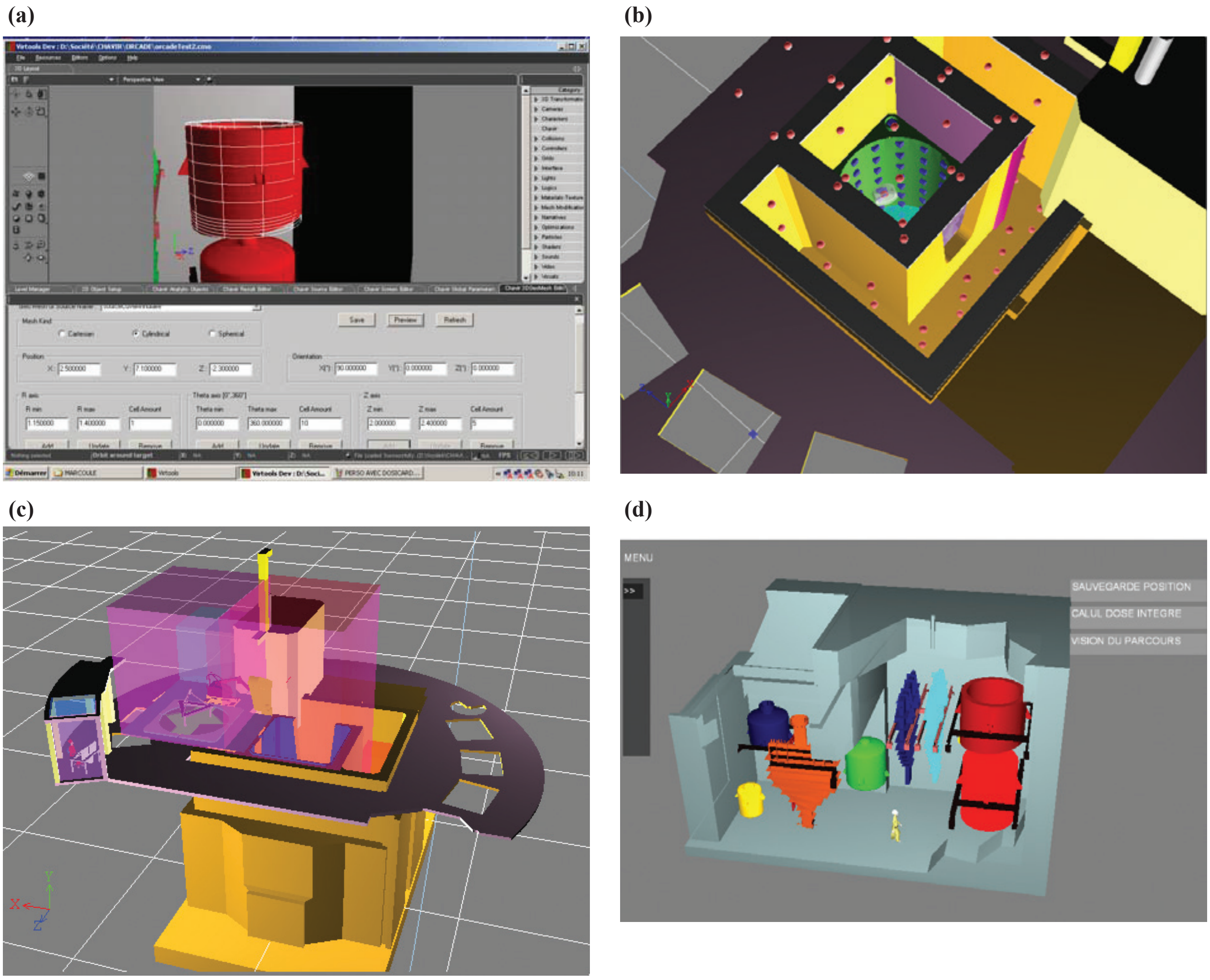


Figure 2. **(a)** Volume source meshing in CHAVIR code; **(b)** Selection of dose rate measurement points in CHAVIR code; **(c)** Simplified visualization model for nuclear power plants in CHAVIR code; **(d)** Visualization model of equipment room in a certain post-treatment plant for CHAVIR code.

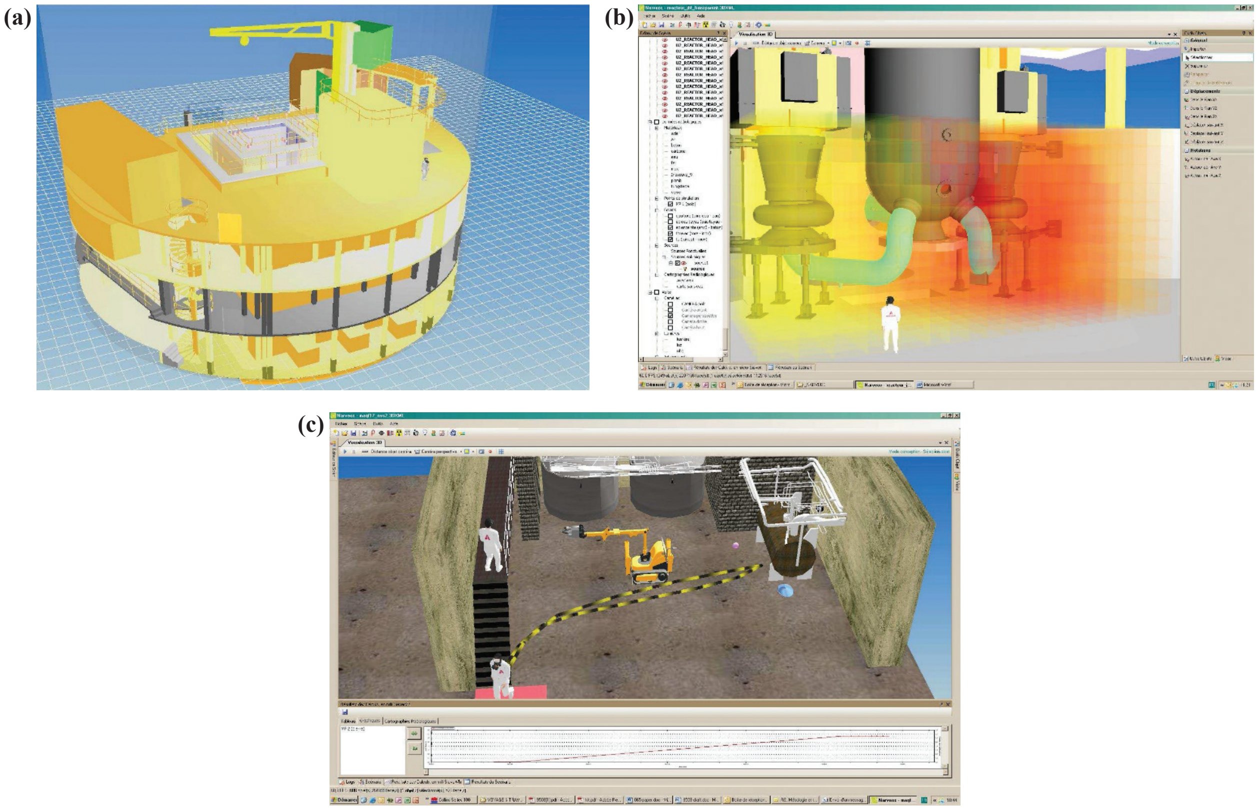


Figure 3. (a) Visualization display of a certain reactor model in NARVEOS code; **(b)** Visualization of the dose field in the personnel operating environment in NARVEOS code; **(c)** Dose rate display in personnel operation path in NARVEOS code.

Visualization of geometry model in PANTHERE code are presented in Fig. 4a, b. The visual display of dose field distribution in PANTHERE is shown in Fig. 4c. A dose optimization module is embedded in PANTHERE and can be used for optimizing work dose in high radiation environments by combining the actual model and the distribution of source terms. PANTHERE code can select certain protective measures to optimize the collective exposure dose and achieve the goal of reducing personnel exposure dose rates. The optimization process is shown in Fig. 4d.

SCK·CEN in Belgium developed VISIPLAN 3D-ALARA software (Vermeersch and Bosstraeten 1998; Vermeersch 2003) that can be used to simulate the dose distribution in decommissioning scenarios based on geometry, material, and source term information. This software adopts the point kernel calculation model to achieve the dynamic calculation of the dose field in three-dimensional scenes. This software can take into account the changes in personnel operation positions, geometry and source terms in the work scene. The scene can be customized for modeling, and there is also an interface to import CAD models. By introducing different shielding structures in the model, the dose field distribution under different shielding materials can be calculated to achieve the development of shielding optimization plans. Detailed planning can achieve the personnel work trajectory simulation and dose assessment. VISIPLAN 3D-ALARA can flexibly edit the radioactive environment and work trajectories to optimize planned tasks. The visualization in VISIPLAN 3D-ALARA can be seen from Fig. 5.

The Japanese Nuclear fuel cycle Development Agency (JNC) and the Japanese Atomic Energy Research Institute (JAERI) developed a decommissioning engineering support system DEXUS (Iguchi et al. 2004) using 3D-CAD, virtual reality (VR) and visualization technology. The system functional modules of DEXUS is shown in Fig. 6. This system is mainly used for the Fugen NPS decommissioning project in Japan. The DEXUS system consists of a database system, evaluation and optimization system, virtual reality and visualization system, and data management system. It can achieve functions such as loading CAD models, dose field calculation, data storage, and visualization display. In addition, the software can also use virtual reality technology to achieve workload simulation for decommissioning plans and demolition plans, worker simulation, safety inspection evaluation and optimization functions. Among them, VRDose (Johnsen and Rindahl 2004) is the main module of the system, which can consider the personnel exposure dose, workload, etc. in the implementation and formulation of nuclear facility retirement plans. VRDose can achieve functions such as dose assessment and optimization of retirement plans, which can be seen in Fig. 6.

In addition, the Korean Atomic Energy Research Institute (KAERI) developed a decommissioning digital simulator system DMU (Digital Mock Up) (Kim et al. 2006), which is mainly used for simulating the decommissioning and dismantling of the KRR-1 reactor. DMU can achieve visual display of simulated decommissioning processes and radiation fields. The DMU system uses the Monte Carlo method to calculate the dose field, including the decommissioning database system, demolition simulation, and data calculation modules, which can be seen in Fig. 7. DMU can import models established by SE (Solid Edge) software and

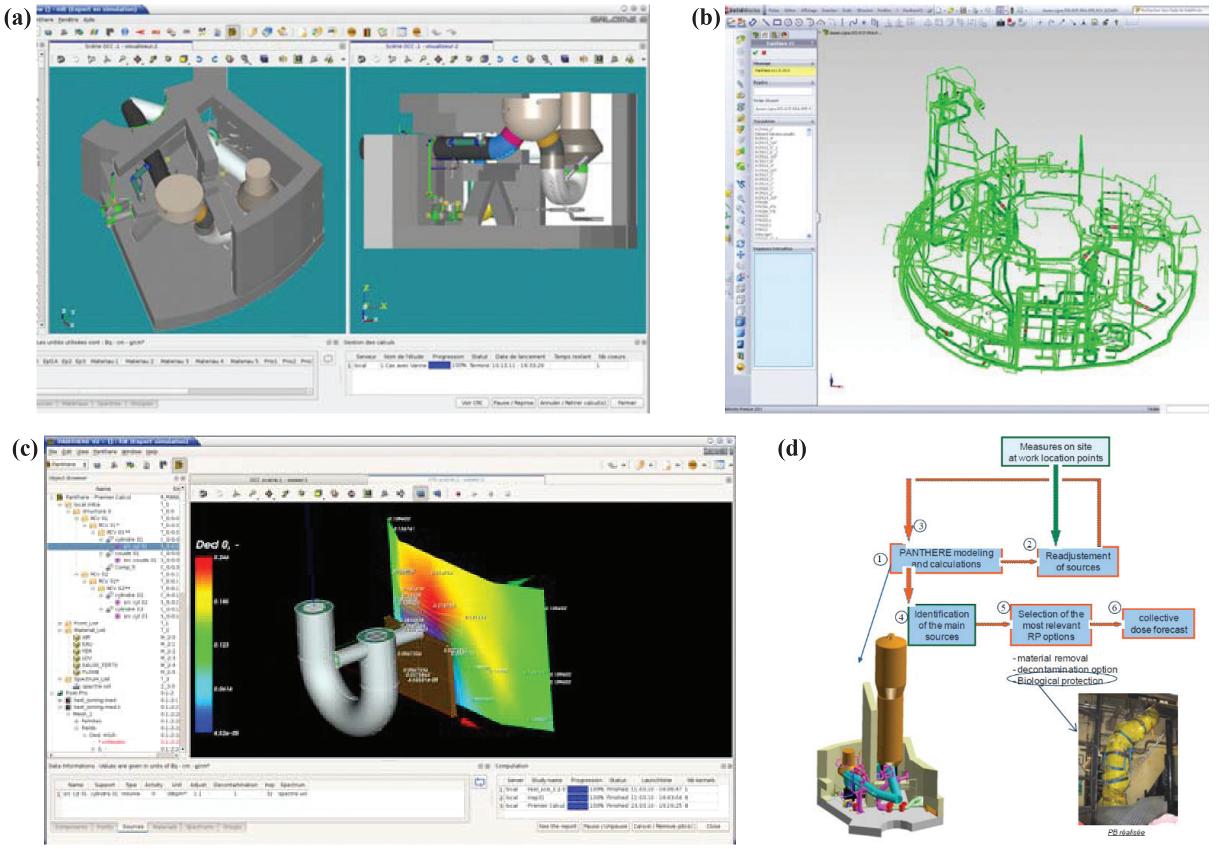
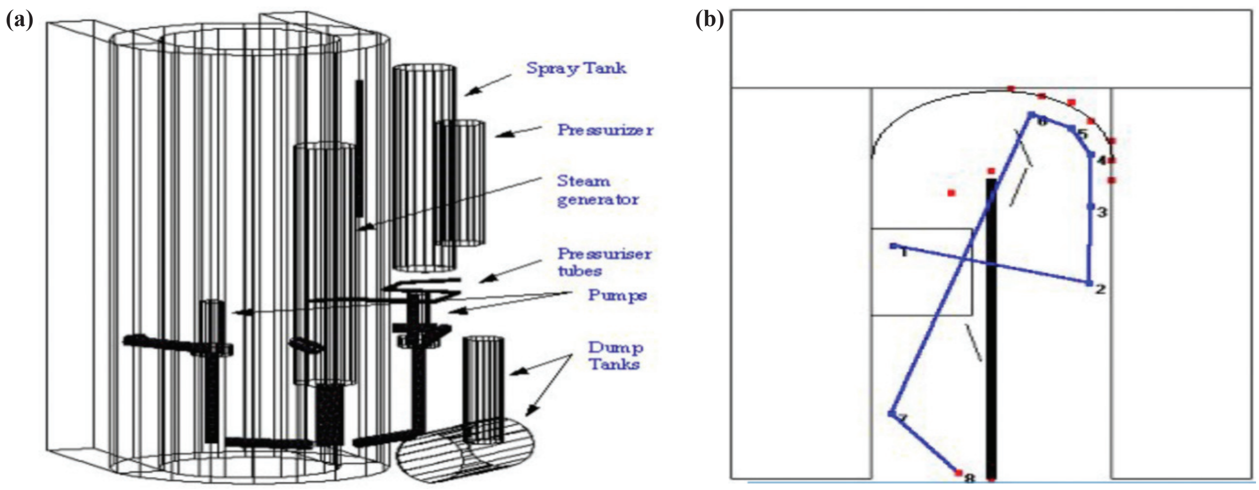
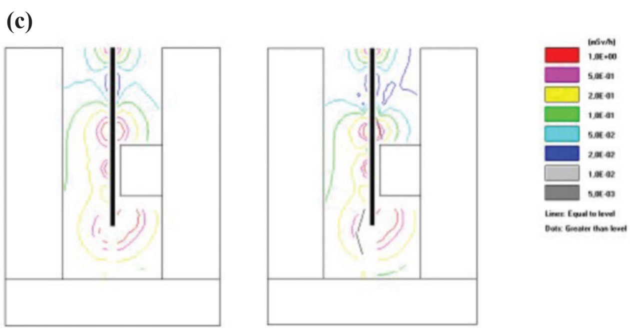


Figure 4. (a) Visualization model of a nuclear power plant in PANTHERE code; **(b)** Pipeline layout model for a nuclear power plant in PANTHERE code; **(c)** Visualization display of dose field in PANTHERE code; **(d)** Radiation optimization process in PANTHERE code.





(d)

Position	work duration (min)	Calculated dose no shielding (mSv)	Calculated dose .5 cm Pb-plates (mSv)	Calculated dose 1 cm Pb-plates (mSv)	Calculated dose 2.5 cm Pb-plates (mSv)	Calculated dose 5 cm Pb-plates (mSv)
A (1)	60	0.120	0.110	0.110	0.110	0.110
B (2)	120	0.220	0.180	0.180	0.150	0.140
C (3)	60	0.130	0.120	0.110	0.077	0.038
D (4)	60	0.130	0.130	0.120	0.079	0.035
E (5)	60	0.130	0.130	0.120	0.078	0.030
F (6)	240	0.570	0.590	0.510	0.230	0.050
G (7)	90	0.070	0.041	0.037	0.031	0.027
H (8)	90	0.180	0.180	0.180	0.180	0.180
Sum	780	1.55	1.48	1.37	0.935	0.610

Figure 5. (a) Building the reactor model in VISIPLAN 3D-ALARA code; **(b)** Setting of personnel work trajectory in VISIPLAN 3D-ALARA code; **(c)** Dose field distribution when selecting different shielding materials in VISIPLAN 3D-ALARA code; **(d)** Calculation of the personnel exposure dose under different shielding materials in VISIPLAN 3D-ALARA code.

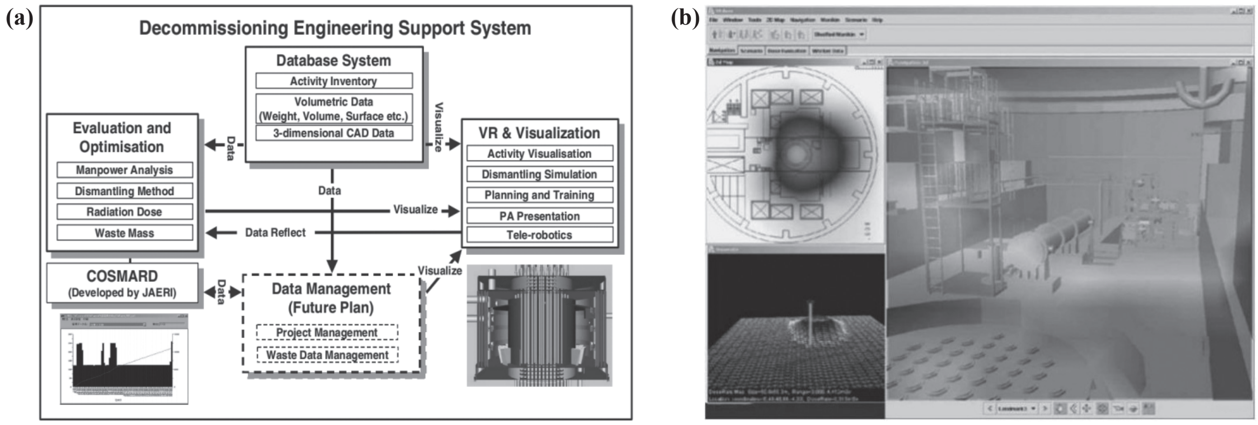


Figure 6. **(a)** System functional modules in DEXUS code; **(b)** Visualization display of a certain scene in DEXUS code.

Figure 7. **(a)** Data management and calculation module of DMU code system; **(b)** Visualization display of model loading and simulation operations in DMU; **(c)** Visualization display of dose field distribution in a certain thermal column in DMU.

3DSM (3D Studio Max) software. DMU can achieve virtual simulation of the decommissioning process in specific scenarios. It can also calculate the demolition time, estimate the demolition cost, optimize the demolition plan. The visualization display of DMU code is shown in Fig. 7. Moreover, some other tools can also be used for 3D dose calculations e.g. MCB code (Oettingen 2020; Cetnar et al. 2021).

In the 1970s, China gradually began to use the computer virtual simulation technology to carry out related technical research in nuclear energy. In recent years, with the rapid development of nuclear energy industry in China, more standardized and professional requirements have been put forward for the technical research and engineering implementation of nuclear facility. Currently, some in-depth research have conducted on the development of virtual simulation technology for nuclear facility decommissioning, including the calculation of dose field and the development of visual display software. Some technologies have also been applied in practice.

The department of computer science and engineering of Beijing Institute of Technology carried out the research on the reactor decommissioning simulation system based on virtual reality (Zheng et al. 2007). The goal of the first stage is to initially realize the radiation dose distribution simulation of the reactor body and surrounding environment. In the mid-term, the main research focuses on waste management, remote operation, and cost estimation for decommissioning. The long-term goal is to achieve the optimization and comparison of retirement plans. The scene construction of simulation system can preliminarily achieve the conversion between VR models, CAD models, and CAE models. Virtual demolition operations can achieve non-destructive and destructive demolition. Virtual decontamination can simulate the operation process and decontamination effect. Virtual operations can enable operators to evaluate workload and exposure dose while walking and operating. The exposure dose is calculated using the point kernel method.

The FDS team of the Institute of Nuclear Safety Technology, Chinese Academy of Sciences developed a general purpose, multi-functional, and accurate nuclear design and radiation safety evaluation software SuperMC (Song et al. 2013; Wu et al. 2015a; Wu et al. 2016). The software uses the Monte Carlo and deterministic methods to support radiation transport, including calculation functions such as burnup, radiation source term, dose, biological hazards, material activation and transmutation. SuperMC can achieve the automatic and accurate conversion from complex engineering CAD models to Monte Carlo computational models. At the same time, it supports the automatic modeling of computational physical properties, achieving the establishment of computational model. SuperMC can achieve complex system modeling and virtual simulation, 3D dynamic data field and model superposition visualization analysis, personnel virtual roaming simulation in nuclear radiation environment. The virtual simulation of dose field in SuperMC can be seen in Fig. 8. At present, the SuperMC software system has been applied to the international thermonuclear experimental reactor program ITER, the lead based reactor ADS-CLEAR of China, the U.S. fusion nuclear science device FNSF, the HPR1000 of China etc (Wu et al. 2015b).

Nuclear Power Institute of China (NPIC) developed a reactor decommissioning simulation system based on the DELMIA and VIRTOOLS software platforms (Dai et al. 2013; Zhang et al. 2018). This system is consists of subsystems such as comprehensive database, virtual scene, retirement process simulation, engineering management. It has the functions such as 3D scene roaming, virtual cutting, demolition process simulation, 3D radiation field visualization, personnel exposure status display, engineering plan and process management, real-time tracking management of radioactive waste. The developed 3D simulation prototype system for reactor decommissioning (Zhang et al. 2018) proposes a 3D radiation field calculation and visualization technology scheme with independent and integrated simulation systems, databases, and kernel methods. The point kernel integration algorithm is used to establish the 3D radiation field calculation model, and the VS language and SQL server software platform are used to prepare the 3D radiation field calculation program. The real-time computing and data update of the 3D radiation field in the retirement scene are realized. The visual display is presented in Fig. 9. At the same time, the calculation method of the personnel radiation dose based on the walking path is proposed. Although the radiation field calculation results of this program have some errors, but the developed 3D radiation field calculation program and the visualization display technology have made initial breakthroughs.

Figure 8. Virtual Simulation of Dose Field in SuperMC.

The Radiation Safety Research Institute of China Institute of Atomic Energy (CIAE) established a three-dimensional radiation field calculation software system (Bi et al. 2015a; Bi et al. 2015b; Bi et al. 2017). The system uses the FLUKA Monte Carlo code and the point kernel integration method to calculate the radiation field. This software includes the CAD based 3D automatic modeling module, radiation source term module, radiation field distribution module, radiation field calculation module, dose simulation and optimization module.

Harbin Engineering University (HEU) established a set of virtual simulation system for nuclear facility decommissioning (Liu et al. 2011). the Unigraphics three-dimensional modeling software is used to establish the three-dimen-

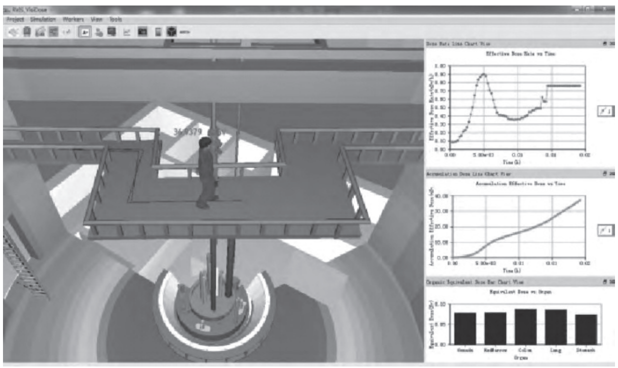


Figure 9. Display of the radiation field distribution in retirement scenarios for reactor decommissioning simulation system developed by NPIC.

sional models of retired personnel and nuclear facilities. C# 4.0 language and Windows Presentation Foundation (WPF) are used to achieve the three-dimensional simulation, scene layout. The manual simulation and automatic optimization using local navigation algorithm can be used to search the optimal path. This system can achieve virtual simulation of three-dimensional scenarios for nuclear facility decommissioning (Chao et al. 2015), which can be seen in Fig. 10.

University of South China developed a rapid and accurate calculation MCPK program for three-dimensional radiation fields and visualization display. This program uses the coupled MCNP5 Monte Carlo code and point kernel method to calculate the dose fields distribution (Guo et al. 2018; Guo 2019), overcoming the shortcomings of long calculation time and insufficient calculation accuracy in shielding calculations. It can achieve rapid and accurate calculation of dose fields. The MCPK program mainly includes a database module capable of customizing information such as scenes, devices, and source items, a radiation field calculation module using Monte Carlo method and point kernel methods, a geometric scenes and dose fields visualization display module, and an interface program module realizing the connection of all calculation processes. The core module of MCPK is the self-developed point kernel calculation module, which establishes various material accumulation factors based on the ICRP data, the database of line attenuation coefficient, photon fluence and conversion coefficient from air kerma in free air to ambient dose equivalent of rays in some elements and materials. In terms of different shielding materials, the geometric identification process of shielding materials and thickness during the radiation transport is considered, which ensures the accuracy and speed of radiation field calculation. The 3D visualization module is mainly developed based on the AnyCAD platform. AnyCAD is a visualization plug-in developed based on Open CASCADE, which is responsible for the display of 3D models and the rendering of radiation exposure fields during the visualization operation. The MCPK code can also achieve dynamic calculation of decontamination and dismantling dose fields, which can be seen in Fig. 11.

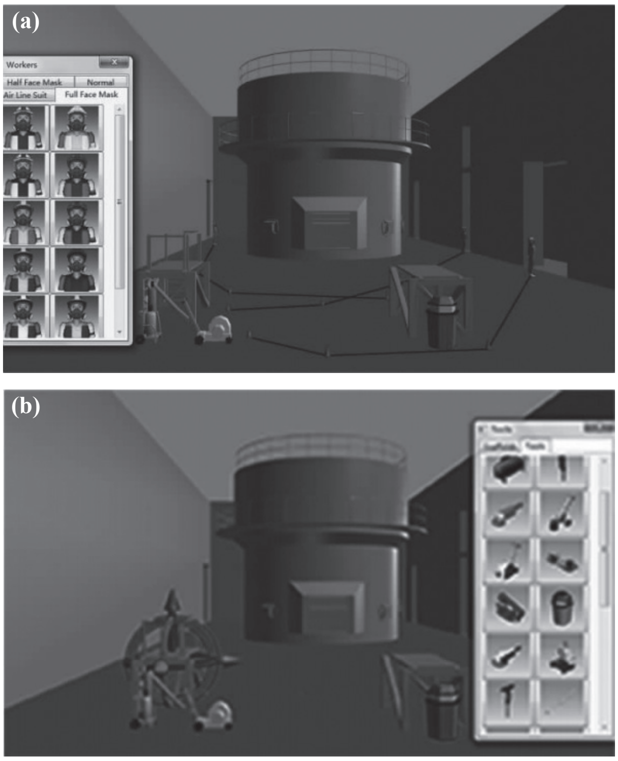


Figure 10. Virtual path setting and simulation scene display in HEU virtual simulation system for nuclear facility decommissioning.

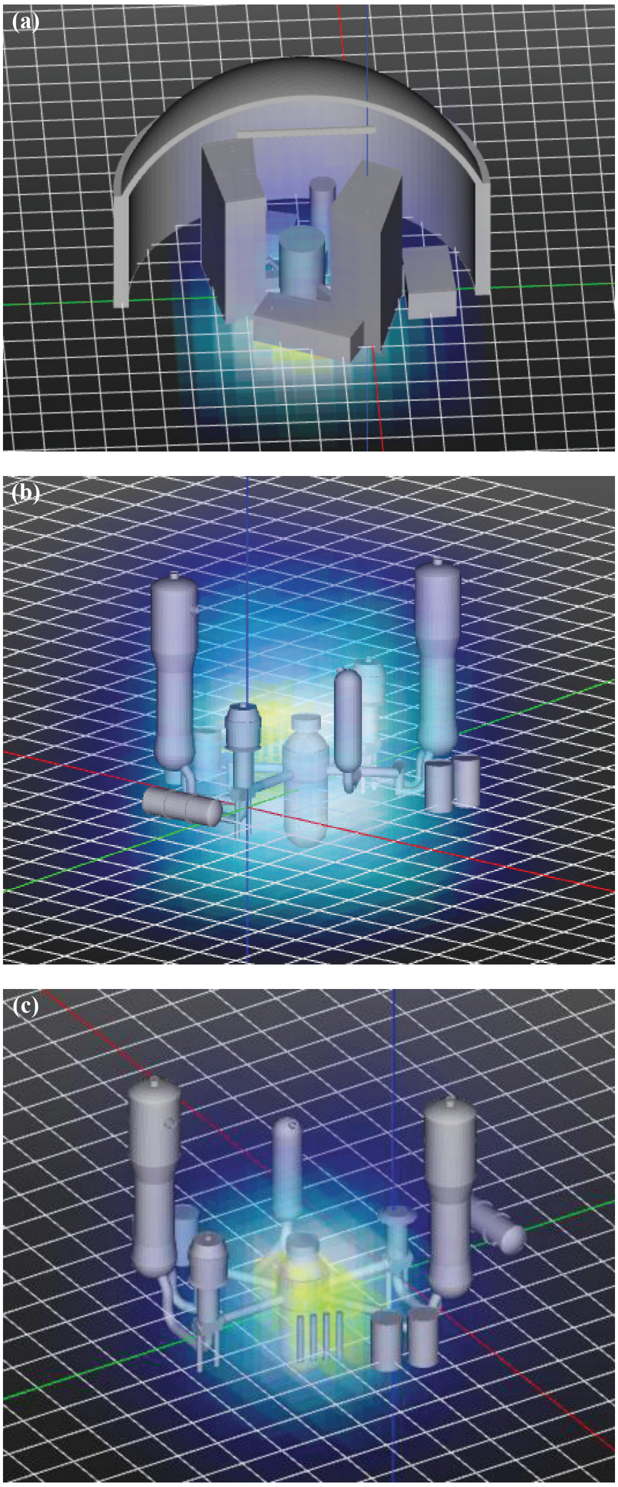


Figure 11. 3D radiation field display in MCPK code system.

Table 1. Dose field virtual simulation systems for reactor decommissioning

Code/Institution	Dose Calculation Method	Features/Function modules
MERCURAD	Point kernel method	shielding material library, cumulative factor calculation, energy group division, dose point definition, dose field calculation, calculation reports
CHAVIR	Point kernel method, Monte Carlo method Coupling method	scenario definition, CAD model, measurement points definition, dynamic calculation of the dose field
NARVEOS	Point kernel method	virtual reality technology, retirement scenario design, rapid dose calculation, 3DVia XM player, dose optimization suggestions
PANTHERE	Point kernel method	custom geometry, CAD geometry, dose under complex source terms, observation points setting, work dose optimization module
VISIPLAN 3D-ALARA	Point kernel method	dose distribution in decommissioning scenarios, dynamic calculation of the dose field, custom geometry, CAD geometry, radiation dose optimization
DEXUS	Point kernel method	3D-CAD, virtual reality (VR), visualization technology, optimized dismantling plan, evaluation and optimization system
DMU	Monte Carlo method	visualization display, data management, calculation module, demolition plan optimization
BIT	Point kernel method	virtual reality, CAD and CAE models, radiation dose distribution simulation, waste management, remote operation, and cost estimation, optimization and comparison of retirement plans
SuperMC	Monte Carlo method	CAD model, dynamic data field and model superposition visualization
NPIC	Point kernel method	DELMIA and VIRTOOLS, 3D scene roaming, virtual cutting, demolition process simulation, 3D radiation field visualization, etc
CIAE	Point kernel method, Monte Carlo method	CAD based 3D automatic modeling, radiation field calculation, dose optimization system
HEU	-	Unigraphics (UG) three-dimensional modeling, work plan optimization
MCPK	Coupling method	AnyCAD platform, rapid and accurate dose calculation
TORT-MCNP	Monte Carlo method, discrete ordinate method	SN calculation module, SN-MC interface module, MC custom source sampling module and MC calculation m odule

In addition, North China Electric Power University developed a TORT-MCNP three-dimensional coupling program system (Han et al. 2012; Han et al. 2014; Han 2012), which is based on the discrete ordinate method (SN) and Monte Carlo method (MC) to calculate the dose field. The TORT-MCNP program combined the advantages of SN method for solving the deep penetration problems and the advantages of MC method in simulating complex geometry. TORT-MCNP system is divided into four main modules: SN calculation module, SN-MC interface module, MC custom source sampling module and MC calculation module. The features or function modules of different dose field virtual simulation systems for reactor decommissioning are summarized in Table 1, the dose calculation method is also presented and compared.

3. Preliminary design of dose field virtual tool for HWRR reactor

3.1. Code development of radiation dose field

The dose field calculation program for the decommissioning of HWRR reactor is mainly used to calculate the radiation field in simulation scenarios, display the decommissioning 3D dose field and estimate personnel exposure dose. Furthermore, the program should provide data support for subsequent decommissioning work and data basis for personnel protection, demolition plans, etc.

3.1.1. Dose field calculation method

Through the preliminary investigation in Section 2, it can be seen that the most commonly methods for calculating the decommissioning dose field are the Monte Carlo method, the discrete ordinate method, and the point kernel method. The specific methodological choices need to be tailored to the characteristics of the problem. In response to the complexity of the HWRR reactor decommissioning scenario, this research intends to develop HWRR reactor decommissioning dose field calculation program by combining mature and user-friendly methods such as the Monte Carlo method, point kernel method, and method of coupling Monte Carlo with point kernel integration (Guo et al. 2018; Guo 2019; Zhang et al. 2021). The considerations are as follows:

(1) Through the investigation, it can been found that there are mature calculation programs and methods for retired dose fields. Most dose field calculation programs are developed using the Monte Carlo method or point kernel method. This indicates that these two methods have strong universality and applicability.
(2) For the development of technical support system for decommissioning engineering of China HWRR reactor, the focus of dose field calculation subsystem is to select appropriate calculation methods, which can meet the requirements for calculation accuracy and speed of different decommissioning scenarios, facilities and equipment, rather than developing new methods. Therefore, the Monte Carlo method and point kernel method can meet most requirements.
(3) The dose field calculation program of the HWRR reactor is planned to create an independent calculation module. The Monte Carlo method is used to achieve accurate dose field calculation for complex source term with no deep penetration problem, the point kernel method is used to achieve fast calculation

of simple source term with thick shielding, and the coupling method is used to achieve fast and accurate calculation of complex source term with deep penetration problem.

(4) For the development of the dose field calculation program, more emphasis needs to be placed on the point kernel method in the overall development. The Monte Carlo programs are mature calculation programs and can be used directly.

the database. If the instruction given by the simulation system is to calculate the changes in the dose field during a certain demolition process, the program needs to determine the impact of the demolition equipment on the overall spatial dose rate, then subtract the demolition dose rate from the initial dose rate, and store the calculation results in the database for subsequent calls. As for the selection of the appropriate calculation method, factors such as the features of application scenarios, computation speed, the

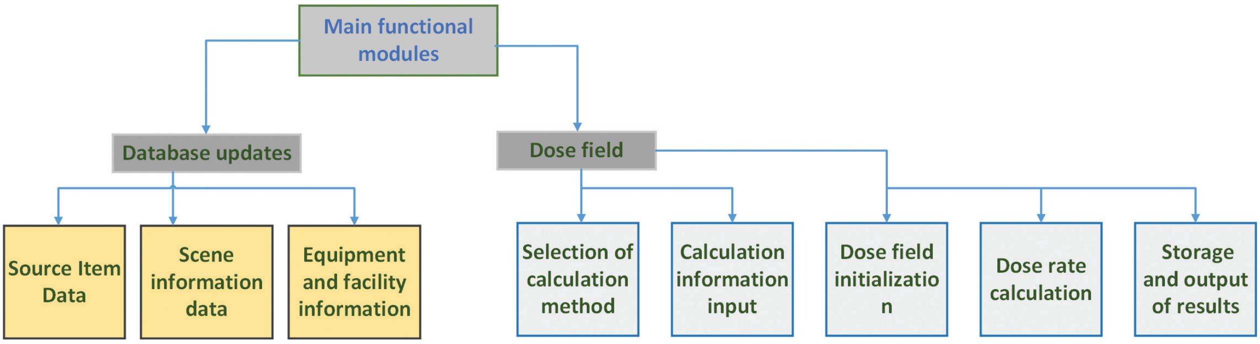


Figure 12. The main functions and module structures of the decommissioning dose field calculation code system for HWRR reactor.

3.1.2. Design and development of code system

The main functions of the decommissioning dose field calculation code system for HWRR reactor include source item data, scene information, facility equipment, and radiation field calculation etc. Users can update the database according to the computational needs. The updates of source item data include the source data input, modification, and viewing of source item data, while the scene information updates should include scene selection, modification, and viewing. The facility and equipment updates include facility and equipment selection, modification, and viewing. As for different retirement scenarios, radiation field calculation should include facilities and equipment information, source terms, the initialization of dose field, the calculation of dose rate, as well as the storage and output of calculation results etc., which can be seen in Fig. 12. Furthermore, the selection of calculation methods such as Monte Carlo method, point kernel method, coupling method also should be considered.

For the different retirement scenarios such as source terms, facilities and equipment, different calculation methods should be chosen to calculate the dose rates of all equipment in their respective spaces. Firstly, the dose field program initializes and calculates the dose rates of all source term devices in all spaces. During the decommissioning simulation process, the main focus is on updating the dose field for the changed scenarios and initializing the dose field for scenarios with significant changes as needed. The calculation process of the dose field calculation program is shown in Fig. 13. After receiving the calculation instruction of the simulation system, the calculation program calls the database information, judges the source items, facilities and equipment of the calculation scene, selects the appropriate calculation method, calculates the scene, and stores the calculation results in

complexity of radiation source term and geometry etc should be comprehensively combined and considered. For example, the Monte Carlo method may be more appropriate for the complex geometry and high-precision radiation field resolution, the point kernel method may be more suitable for the scenario that the radiation field data needs to be given quickly and the precision for radiation field data is low. For the scenarios that need to provide radiation field data quickly with relatively high accuracy, the coupling method of Monte Carlo and point kernel method can be considered for calculation.

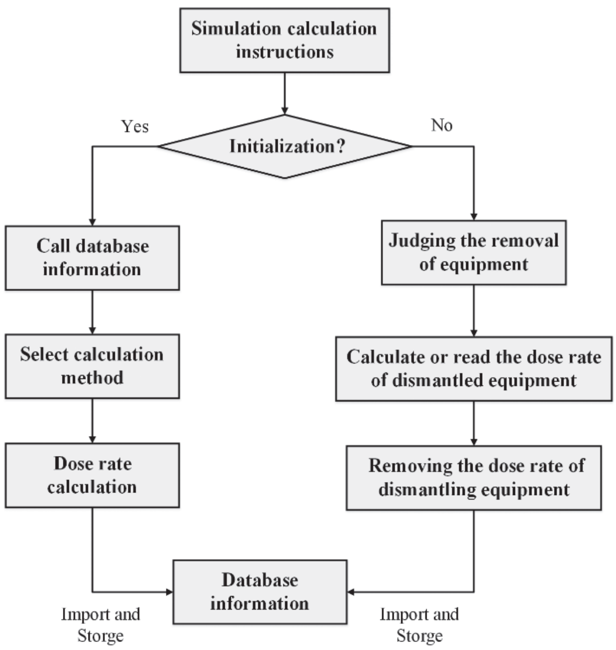


Figure 13. The calculation process of the dose field calculation program for HWRR reactor.

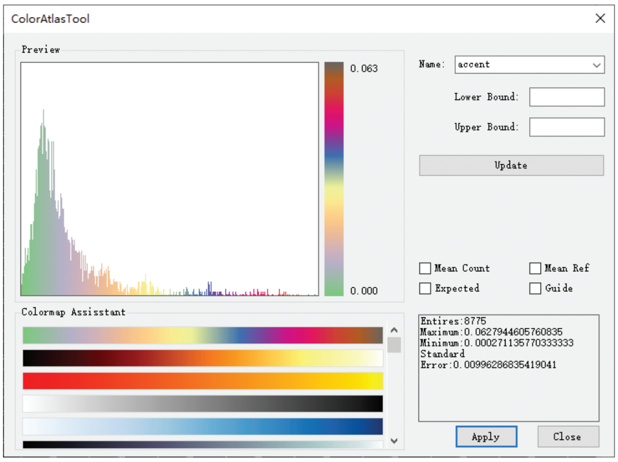


Figure 14. The interface of chromatography tool for dose field and virtual system of HWRR reactor.

visualization interface. If the displayed color of the dose field does not meet the needs, the chromatography tool should be used to set, the interface of chromatography tool is shown in Fig. 14.

3.3. Calculation and visual display of the dose field for outer shell of HWRR reactor

3.3.1. HWRR reactor

The Heavy Water Research Reactor is the first large research reactor to be decommissioned in China (Ren et al. 2023). The main body of HWRR reactor adopts the multi-layer canister structure. The Fig. 15 shows the main structure of HWRR reactor. The central area is the active zone of the reactor body where the fuel assemblies are loaded. The graphite reflection layer, shielding water tank, packing sand layer and shielding layer are arranged outward successively.

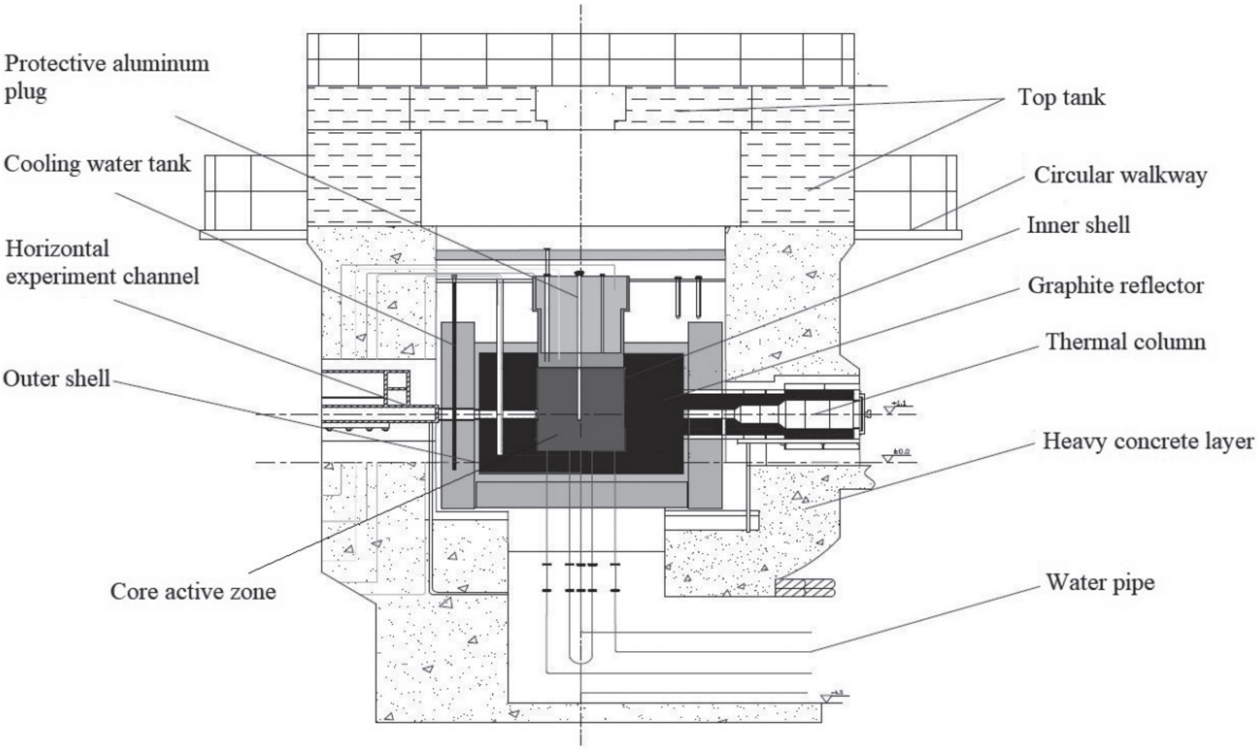


Figure 15. The main structure of the HWRR reactor.

3.2. Visualization implementation

Unity 3D is a virtual reality engine mainly used for realistic display of scene models and data. Based on the Unity 3D software, the dose field visualization display module is developed, so that it is easy for users to operate and use. It can perform visualization display of dose fields. The dose field visualization module is intended to consist of a menu bar and a visualization window, which includes files, views, windows, and help button.

The visualization of dose field is divided into two steps. Firstly, the users should import the STL and STEP files of the scene and then import the TXT or EXCEL data files of the dose field data. After the program successfully read the dose field file, the dose field will present in the

The outer shell of HWRR reactor consists of three cylinders of different diameters welded together with two ring plates, a bottom plate and a flange. The structure of outer shell is shown in Fig. 16. There are 44 screw holes on the end face of the cylinder for installing the sealing flange, and another through hole for installing the vertical test hole of the graphite layer. The size of the upper barrel is 1675 mm in outer diameter and 15 mm in wall thickness, the size of the middle barrel is 1470 mm in outer diameter and 20 mm in wall thickness. A stiffener plate is welded around the middle barrel to improve the overall rigidity of the shell. The size of the lower barrel is 2690 mm in outer diameter and 15 mm in wall thickness. The bottom of the

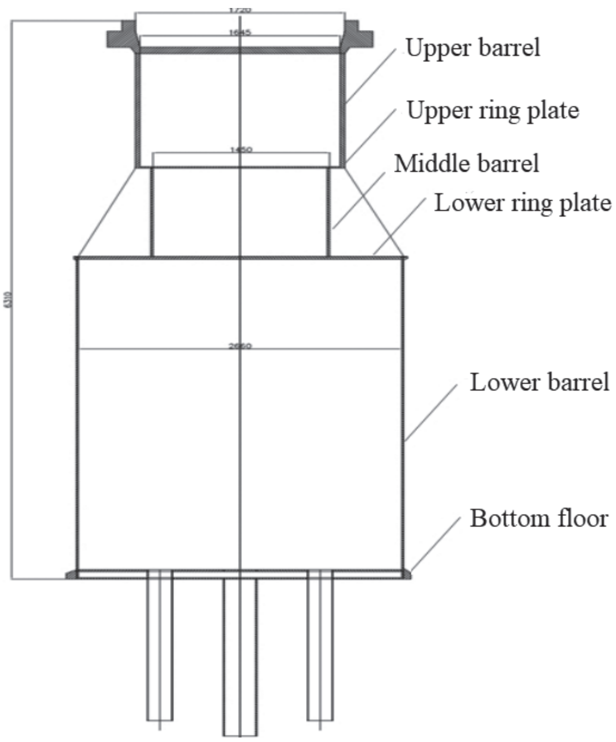


Figure 16. The structure of the outer shell of HWRR reactor.

outer shell is made of two layers of welded steel plates, the two layers are supported by steel beams. Table 2 provides the detailed dimension of the outer shell of HWRR reactor.

3.3.2. Dose field of HWRR reactor outer shell

The source term data of outer shell is preliminarily estimated by the ORIGEN2.1 code based on the historical power data of HWRR reactor, then these data is provided to the the coupling method of Monte Carlo method and point kernel method, so the dose field distribution of the HWRR outer shell can be obtained. The preliminary designed virtual simulation program of HWRR reactor uses Pro/E to build the 3D model. The visualization of dose field can be displayed after loading the dose field data. Fig. 17 shows the visual display of the dose field of the HWRR reactor outer shell. The capability of geometry processing and dose field visualization are preliminarily verified, it can initially be used to support HWRR decommissioning.

Table 2. The dimension of the outer shell of HWRR reactor

Component	Outer diameter (mm)	Inner diameter (mm)	Wall thickness (mm)	Height (mm)
Upper barrel	1675	1645	15	1650
Middle barrel	1470	1430	20	1130
Lower barrel	2690	2660	15	3280
Lower ring plate	2735	-	30	-
Upper ring plate	2660	-	30	-
Bottom floor	2730	-	30	-

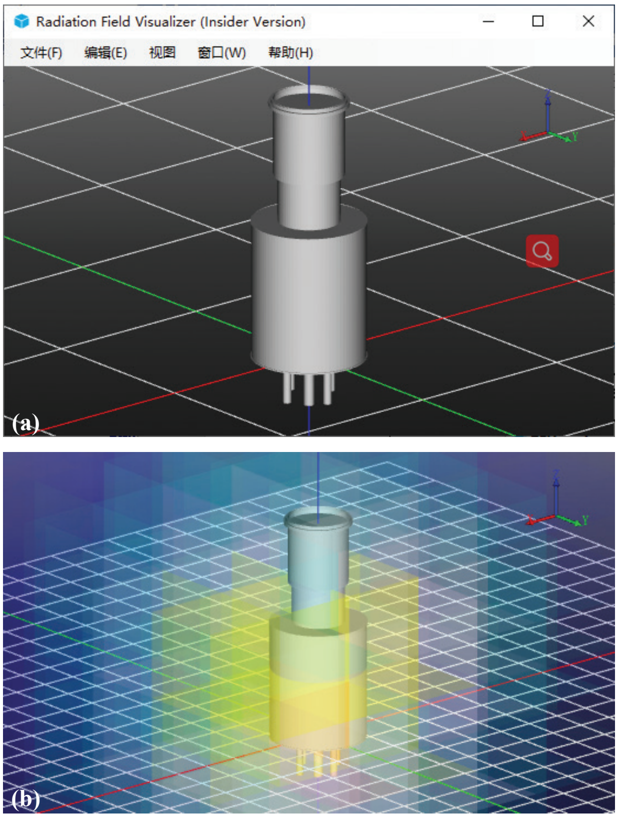


Figure 17. (a) Outer shell model of HWRR reactor; **(b)** Visualization display of dose field of HWRR reactor.

4. Conclusions

Dose filed virtual simulation system is a powerful auxiliary tool for the decommissioning engineering, which can provide a support platform for the determination of decommissioning implementation scheme, optimization of the process planning and personnel training, etc. The calculation and visualization of 3D radiation field in the decommissioning scene is one of the important functions for the reactor decommissioning virtual simulation system. This kernel module can provide accurate and intuitive radiation field distribution in the design of decommissioning scheme, and play an important role in the protection of personnel in engineering implementation. Therefore, this paper investigates and summarizes the progress of relevant technologies in the dose filed virtual simulation system for reactor decommissioning, and initially proposes the technical scheme suitable for the development of dose field calculation and visualization tool for the decommissioning work of the first HWRR reactor in China. The applicability of the technical scheme is analyzed, and the outer shell of the HWRR reactor is modeled and the dose field distribution is visualized. This work can provide technical support for the subsequent development of virtual simulation system for the decommissioning of HWRR reactor.

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