# Feasibility Study on Three-Dimensional Radiation Field Reconstruction Technology for Nuclear Power Plants

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## Abstract

Three-dimensional radiation field reconstruction technology can obtain the spatial distribution of radioactive materials and three-dimensional radiation dose fields. Combined with three-dimensional building point cloud information in the radiation imaging space, it enables clear and unambiguous three-dimensional visual observation of the distribution and dose fields of unknown radiation sources or radioactive materials. In nuclear power plants, the complex spatial layout of radiation source terms, characterized by large variations in radiation field levels across different regions, complex shielding structures, and the inability to perform exhaustive measurements, has resulted in the absence of relevant applications of three-dimensional radiation field reconstruction technology domestically to date. This paper compares the current development status of three-dimensional radiation reconstruction research both domestically and internationally, analyzes the feasibility of implementing plant-wide real-time three-dimensional radiation field reconstruction applications in nuclear power plants from four aspects: geometric modeling, source term localization and quantification, radiation field calculation, and three-dimensional visual simulation, and provides solution-oriented approaches for enhancing radiation safety management in nuclear power plants from the perspective of intelligent and digital applications.

## Full Text

## Feasibility Study on Three-Dimensional Radiation Field Reconstruction Technology for Nuclear Power Plants

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### Abstract

Three-dimensional radiation field reconstruction technology can obtain the spatial distribution of radioactive materials and generate three-dimensional radiation dose fields. When combined with three-dimensional point cloud data of building structures within the radiation imaging space, this technology enables clear and intuitive visualization of unknown radiation sources or radioactive material distributions and their associated dose fields. Due to the complex spatial layout of radiation source terms, significant variations in radiation levels across different areas, intricate shielding structures, and the inability to conduct comprehensive measurements throughout nuclear power plants, relevant applications of three-dimensional radiation field reconstruction technology have not yet been implemented domestically. This paper compares the current research and development status of three-dimensional radiation reconstruction both domestically and internationally, and analyzes the feasibility of implementing real-time, plant-wide three-dimensional radiation field reconstruction in nuclear power plants from four aspects: geometric modeling, source term localization and quantification, radiation field calculation, and three-dimensional visualization simulation. The study provides solutions for enhancing radiation safety management in nuclear power plants from the perspective of intelligent and digital applications.

**Keywords:** Three-dimensional radiation field; Nuclear power plants; Radiation protection

### Introduction

Currently, radiation monitoring in nuclear power plants relies on manual measurements using portable radiation detection equipment, which can only obtain radiation information at single locations at specific times within accessible areas. This approach cannot achieve globalized and real-time monitoring of radiation information and historical data across the entire plant, leading to imprecise identification of radiation risks and discrepancies between actual and estimated radiation risks, thereby increasing the risk of unplanned exposures. Additionally, manual measurement increases operational risks and radiation doses for workers, which is detrimental to collective dose control and optimization efforts.

In fields such as nuclear facility decommissioning and decontamination surveys, special nuclear material detection at customs ports, and radiation source searching, numerous research institutions have conducted studies on three-dimensional localization of radiation sources and three-dimensional radiation field calculations. These efforts include source term localization based on counting detectors and gamma imaging devices, as well as dose field calculations using point kernel integration algorithms. However, current three-dimensional radiation modeling and dose field construction in nuclear power plants are mostly conducted independently or for partial equipment and localized areas as static dose monitoring. The processes of radiation measurement, radiation field calculation, data analysis, and application involve numerous steps that are not well integrated, and plant-wide real-time three-dimensional radiation field applications have not been realized. This paper analyzes the feasibility of implementing real-time three-dimensional radiation field reconstruction technology in nuclear power plants based on existing three-dimensional radiation field technologies and the characteristics of radiation source terms in nuclear power plant buildings.

## 2. Characteristics of Radiation Source Terms in Nuclear Power Plants

During reactor operation in nuclear power plants, radiation source terms originate primarily from two sources. First, the fission process in reactor fuel produces large quantities of radioactive fission products. In high-temperature environments, these fission products are released from fuel pellets into the gap between the fuel pellets and cladding through diffusion mechanisms, and then enter the reactor coolant through microscopic defects (small holes, cracks, or damage) in the fuel rod cladding. Second, metallic materials in contact with the coolant undergo corrosion and erosion, releasing corrosion products in particulate form. These products become radioactive activation products after irradiation in the core, and when deposited on the inner surfaces of systems and equipment inside and outside the reactor, they become radiation sources.

Due to the migration characteristics of radiation source terms with coolant in nuclear power plants, all primary loop-related systems possess certain levels of radioactivity, with deposits easily forming in areas with flow resistance such as equipment, valves, and pipe bends, resulting in significant variations in radioactivity levels at different locations. Concurrently, the numerous pipelines and equipment and their complex spatial layout ultimately manifest as a complex spatial distribution of radiation source terms in the plant, posing substantial challenges for three-dimensional geometric modeling, measurement, and calculation.

Therefore, the main difficulties in implementing real-time three-dimensional radiation field reconstruction for nuclear power plants include: first, using undersampled real-time radiation measurement information to perform inverse calculations of dose fields under conditions of large radiation level variations across different areas, complex shielding structures, and the inability to conduct comprehensive measurements, in order to accurately calculate true dose rates in non-measurable regions; and second, generating radiation field data covering the entire scene from scattered data points to enable rapid registration of three-dimensional dose field data with the plant geometric scene model, achieving the dual objectives of data and location accuracy.

## 3. Research Status of Three-Dimensional Radiation Field Technology

### 3.1 Geometric Modeling

Traditional radiation field modeling generally requires manual drawing based on plant room and equipment dimensions as input, which increases the probability of human error. With the continuous development of computer applications, new technologies such as reverse engineering have emerged and begun to be applied across various industries. Three-dimensional laser scanning technology is a rapidly developing technique that measures high-density and high-precision three-dimensional coordinates of actual building surfaces by emitting laser pulse signals and returns massive point cloud data. Through further processing of this point cloud data, complex real-world scenes can be rapidly obtained. Compared with traditional modeling techniques, three-dimensional laser scanning technology offers distinct advantages: (1) rapid acquisition of model data with real-time access to high-precision data; (2) high autonomy, capable of independently completing data measurement tasks; and (3) comprehensive data information facilitating easy post-processing.

### 3.2 Source Term Localization and Quantification

The accuracy of source term information measurement directly determines the precision of three-dimensional radiation field reconstruction. Radioactive materials in nuclear power plant buildings are mostly distributed in known objects such as pipelines and equipment. By measuring the dose rate levels, radiation source positions, and source strength levels of these objects, specific spatial localization and quantification of source terms can be achieved. Currently, dose rate measurement methods in the nuclear power radiation protection field are relatively mature, with detector measurement ranges covering levels from nSv/h to Sv/h. Additionally, wide-range radiation detectors developed by the Institute of High Energy Physics, Chinese Academy of Sciences can effectively detect gamma photons from tens to thousands of electron volts, enabling identification of characteristic energy peaks of radionuclides, which well satisfies source term measurement requirements.

For radiation source localization, gamma cameras are currently widely adopted in the industry. These devices generate images by capturing scattered radiation signals through detectors. Compared with conventional optical cameras, gamma cameras can penetrate heavy objects without being affected by obstructions, and they offer higher resolution capable of capturing subtle radiation variations. However, gamma cameras currently used in domestic nuclear power plants are primarily imported products. With the advancement of domestic technology in recent years, several domestic research institutions have completed independent localization of gamma cameras, providing technical assurance for subsequent three-dimensional radiation field reconstruction.

### 3.3 Radiation Field Calculation

In nuclear power plants, source term acquisition is typically obtained by experienced personnel through accumulated experience or by on-site radiation protection staff through measurements. Currently, the main methods used domestically and internationally for radiation dose field distribution calculations are the Monte Carlo (MC) method and the point kernel integration method.

The MC method, also known as the random sampling method, is a probability-based numerical statistical method commonly used to simulate radiation dose fields. This method is relatively mature in the field of radiation physics and can accurately simulate dose distributions in radiation fields, particularly suitable for complex radiation fields and shielding environments. However, this method relies on statistical sampling to simulate the random motion and interaction processes of particles, requiring large statistical samples to obtain relatively accurate dose distributions, which results in slow convergence speeds. Certain model calculations often require several hours or even days, making it suitable for simulating dose fields in locally complex scenarios such as densely packed pipeline areas.

The point kernel integration method employs numerical analytical approaches for dose field calculation. It is not limited by spatial geometric dimensions or radiation source shielding thickness and features small computational loads and extremely fast calculation speeds. However, due to Compton scattering effects during ray propagation, lower-energy rays become dispersed, requiring calibration of weighting factors for gamma rays of different energies at the same dose calculation point—namely, buildup factors. Consequently, this method constitutes an empirical radiation calculation approach whose primary weakness lies in relatively lower calculation accuracy. Additionally, it can only calculate dose rate values at limited points at one time, significantly limiting the computational efficiency for large-scale radiation fields. Moreover, point kernel integration generally employs single-threaded computation modes, which wastes the processing capabilities of commonly available multi-core computers.

Therefore, combining Monte Carlo simulation and point kernel integration methods provides an approach to accurately calculate radiation dose fields. Monte Carlo simulation is suitable for calculating locally small-scale complex shielding scenarios, while point kernel integration is applicable for large-scale spatial calculations. This combination can effectively address the requirements of nuclear power plants for both calculation accuracy and response time.

### 3.4 Three-Dimensional Visualization Simulation

Currently, nuclear power plants primarily rely on physical operational methods to increase worker proficiency and accumulate work experience, which also leads to increased worker radiation exposure. With the development of computer computing power, three-dimensional visualization simulation technology has found mature applications in medical, transportation, exploration, film, and other fields. Radiation field visualization technology can integrate radiation protection technology with virtual simulation computer technology, obtaining more comprehensive and accurate radiation information through the integration and fusion of different data sources, and ultimately achieving automatic identification and classification of radiation risks through advanced artificial intelligence algorithms learning from large sample datasets.

Furthermore, graphics processing units (GPUs) used in three-dimensional rendering have undergone significant development in recent years. Compared with traditional CPUs, GPUs lack large control units and instead enhance graphics processing performance and memory bandwidth by increasing execution units and memory control units. GPUs have been widely applied in gaming, virtual reality, scientific computing, artificial intelligence, and other fields, providing a feasible solution for implementing real-time three-dimensional radiation field reconstruction across the entire plant in nuclear power plants.

## 4. Application Status in Related Fields Domestically and Internationally

### 4.1 Domestic Research Status

Currently, computer visualization technology has developed to a very mature stage in China, and nuclear power plant radiation protection theory is also relatively mature. However, the combination of these two technologies is just beginning, with few practical applications. From the perspective of international research status, radiation field measurement and reconstruction technology and virtual reality technology have numerous application cases and are widely used in radiation risk analysis and radiation dose assessment.

In China, virtual reality (VR) technology has been widely applied across various industries. The Wuhan Institute of Nuclear Power Operations has independently developed a simulation system based on VR technology for simulating maintenance scenarios in nuclear power plants. Within the nuclear power industry, the Daya Bay Nuclear Power Base and the Hongyanhe Nuclear Power Plant have both completed VR training room construction for safety-related training and experience. Trainees gain immersive and profound experiences through VR-based training, with training effectiveness in operational safety risk communication and accident warning education significantly superior to traditional classroom and hands-on training.

The FDS team of the Chinese Academy of Sciences has developed the SuperMC nuclear and radiation safety simulation system for nuclear power plants, based on advanced technologies including computer digital reactors and virtual human models in radiation environments, combined with their independently developed high-precision Chinese adult radiation virtual human model Rad-MUMAN. This system features result modeling and assembly functions, radiation field data visualization capabilities, and nuclear radiation personnel operation simulation and virtual roaming functions. It has been preliminarily applied to radiation field evaluation and simulation for ITER fusion reactor maintenance and CLEAR-I spallation target replacement in China' s experimental reactor, with plans for subsequent application in reactor design and optimization, nuclear power plant maintenance, personnel training, and science education. Additionally, some domestic universities and research institutes have conducted relevant research on the point kernel integration method and achieved certain results, such as the three-dimensional radiation field calculation program developed by Harbin Engineering University based on the QAD program, the JMCT-PK point kernel integration gamma dose calculation software developed by the China Academy of Engineering Physics, and the DeepP three-dimensional radiation field calculation program based on point kernel integration developed by Tsinghua University. All these developments provide technical assurance for implementing real-time three-dimensional radiation field reconstruction technology in nuclear power plants.

### 4.2 International Research Status

In Western developed countries, where computer technology development started earlier, radiation field measurement and reconstruction technology and virtual reality technology have long been applied in nuclear power plant radiation protection fields, primarily for dose assessment, path optimization, personnel training, and maintenance plan formulation.

The Oak Ridge National Laboratory in the United States has developed the QAD series program based on the point kernel integration algorithm, enabling rapid calculation of radiation quantities such as particle fluence rates and dose rates. The French Atomic Energy Commission (CEA) has developed MERCURAD, CHAVIR, NARVEOS, and other point kernel integration program tools based on virtual reality. VISIPLAN3D-ALARA for radiation assessment in nuclear facility decommissioning scenarios employs algorithms based on point kernel integration and buildup factor correction to simulate and calculate radiation fields in nuclear power plants. Spain has developed the CIPRES system specifically for simulating and calculating radiation levels during nuclear power plant refueling processes. To simulate nuclear facility decommissioning processes and calculate environmental radiation levels, the Japan Atomic Energy Agency has developed the VRdose program based on the point kernel integration algorithm.

## 5. Conclusions and Outlook

This paper aims to implement real-time three-dimensional radiation field reconstruction technology in nuclear power plants and analyzes the feasibility of implementing such reconstruction from four aspects: geometric modeling, source term localization and quantification, radiation field calculation, and three-dimensional visualization simulation. By comparing domestic and international research and development status, the study concludes that implementing plant-wide real-time three-dimensional radiation field reconstruction applications in nuclear power plants is currently feasible. The application of three-dimensional radiation field technology will significantly reduce on-site radiation measurement work, avoid risk estimation based on empirical judgment of field radiation levels, and resolve discrepancies between estimated and actual radiation levels. Simultaneously, through real-time monitoring to formulate optimized control measures, operational risks can be controlled, personnel doses reduced, and radiation safety levels in nuclear power plants improved. Comprehensive application can achieve the goals of reducing staff while increasing efficiency and improving economic benefits.

The application of real-time three-dimensional radiation field reconstruction integrates multiple fields including computer-aided design, graphic design, radiation protection, virtual simulation, and human-computer interaction, among which source term localization and quantification and radiation field calculation are critical implementation aspects that require substantial subsequent effort. Specific challenges include: (1) The lack of actual data for comparison in nuclear power plant radiation field calculations necessitates extensive experimental validation in the future to improve calculation accuracy; and (2) Overcoming the trade-off constraint between sensitivity and resolution in source term quantification measurements still requires research and innovation in measurement methodologies.

### References

[1] Tang Shaohua, Lü Weifeng, Liu Jie, Xiong Jun, and Huang Qianqian, "Development and Application of a Three-Dimensional Dose Field Evaluation System for Nuclear Power Plants," *Radiation Protection*, vol. 37, no. 5, pp. 347–354, 2021.

[2] Liu Xinhua, *Primary Loop Source Term and Emission Source Term of Nuclear Power Plants.* Beijing: Science Press, 2019.

[3] Li Chunhuai, "Review of Radiation Shielding Design Methods for Reactor Primary Loop Equipment Rooms," *Nuclear Power Engineering*, 2003, 24(5).

[4] He Tao, *Research on Integrated Simulation Methods and Technologies for Nuclear and Radiation Safety* [D]. Hefei: University of Science and Technology of China, 2014.

[5] Mol ACA, Jorge CAF, Couto PM, et al. Virtual environments simulation for

dose assessment in nuclear plants[J]. *Progress in Nuclear Energy*, 2009, 51(2).

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