Research and Development Status of Mobile Hot Cells at Home and Abroad

Authors: Zhu Haoyuan, Wang Huacai

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Abstract

A mobile hot cell is a radioactive material processing facility that can be transported integrally and rapidly reassembled at target sites, addressing the limitations of poor flexibility and mobility inherent in conventional fixed hot cells through modular design. With the continuous development of the nuclear industry, nuclear facilities face growing demands for radioactive material operation and conditioning. While conventional fixed hot cells represent mature technology, their inherent immobility and high costs constrain their application scope. As an innovative nuclear facility, mobile hot cells offer advantages including lightweight construction, disassemblability, high mobility, and cost-effectiveness, enabling rapid response to inspection and processing requirements at nuclear facilities. This paper provides an overview of the development trajectory of mobile hot cell facilities with diverse structures both domestically and internationally, reviewing research progress and achievements from first-generation mobile hot cell designs to contemporary studies by various institutions worldwide. The current research status regarding shielding methods, viewing windows, transfer containers, and other components is systematically summarized. The article identifies multi-module sealed interconnection, high-efficiency shielding integration, and intelligent operation and maintenance as pivotal future development trends for mobile hot cells.

Full Text

1 Introduction

Hot cells are shielded enclosures designed for conducting experiments and operations with highly radioactive materials in isolation from the surrounding environment, thereby ensuring personnel protection from radioisotope hazards. These facilities play a critical role in spent fuel inspection, verification of material irradiation performance, and radiochemical experiments. Conventional hot cells are typically constructed as integral components of nuclear facility buildings, employing thick heavy concrete walls for radiation shielding. Operators observe and manipulate objects inside the hot cell through viewing windows and cameras while using master-slave manipulators from outside the cell, with a series of auxiliary systems ensuring both operator safety and containment of radioactive materials. Globally, hot cell facilities have found widespread application, with the number of post-irradiation examination hot cells in selected countries shown in Table 1 .

When no supporting hot cell facilities are available near a nuclear installation, radioactive materials must be packaged and transported to hot cells in other locations. However, nuclear facilities in remote areas often face transportation challenges that impede rapid response to inspection requirements. To address this limitation, mobile hot cells have emerged as an innovative solution. Unlike traditional stationary hot cells, mobile hot cells utilize relatively lightweight, detachable wall structures as their main body. These facilities can be disassembled into modules, transported to designated locations, and reassembled, offering superior mobility and flexibility. Compared to fixed hot cells, mobile hot cells feature lower construction costs, enable rapid response to inspection and processing needs at nuclear facilities, and can provide radioactive operation and inspection capabilities for facilities lacking hot cell construction conditions, such as remote nuclear reactors, offshore drilling platform reactors, and non-stationary nuclear installations like marine reactors and nuclear submarines, as illustrated in Figure 1 [Figure 1: see original paper]. A structural schematic of a mobile hot cell is presented in Figure 2 [Figure 2: see original paper].

2 Main Structure

The design of mobile hot cells must first establish clear functional requirements. Functionally, existing mobile hot cells fall into two primary categories: waste radiation source conditioning hot cells and post-irradiation examination hot cells. The former category includes the mobile hot cell jointly developed by the IAEA and South Africa' s Nesca [9] and the mobile waste radioactive source conditioning device designed by the China Institute for Radiation Protection [5]. These systems are primarily used for collecting and conditioning discarded industrial or medical radioactive sources, transferring them from original storage containers into new containers suitable for transport and storage, which can then be shipped to licensed facilities for centralized storage and disposal, thereby reducing risks to public safety and environmental contamination. Post-irradiation examination mobile hot cells include the mobile shielded inspection hot cell designed by the China Nuclear Power Technology Research Institute [2], which provides temporary inspection capabilities for nuclear power plant components under emergency conditions. The main structure of a mobile hot cell comprises a base, outer walls, shielding modules, viewing windows, master-slave manipulators, and other primary unit modules, supplemented by auxiliary systems such as video monitoring, radiation monitoring, transfer systems, and ventilation.

2.1 Shielding Walls

Shielding design must first identify the types, quantities, sizes, and geometries of radionuclides to be handled, along with the anticipated activity types and radiation levels. Primary considerations include actinides such as U, Pu, and Np that emit alpha particles and neutrons; beta-emitting radionuclides including 90Sr, 90Y, 137Cs, and 60Co; and gamma-emitting radionuclides such as 137Ba and 60Co [16]. Post-irradiation examination hot cells primarily handle inspection of irradiated fuel, cladding, and structural materials, whereas waste radioactive source conditioning hot cells mainly process radioactive isotopes. Shielding structures and transfer channels must be designed according to these specific handling requirements. Based on the radiation types to be shielded, hot cells can be classified into two main categories: β-γ hot cells and α-β-γ hot cells. Both types provide shielding against beta, gamma, or neutron radiation, but differ in their sealing requirements—β-γ hot cells are relatively sealed, while α-β-γ hot cells demand complete sealing. Mobile hot cell sealing design should reference standards EJ/T 1096-1999 "Sealed Enclosure Classification and Test Methods for Sealing Performance" and EJ/T 1108-2001 "Design Principles for Sealed Enclosures."

Traditional shielding materials include water, lead, concrete, and stainless steel. Water is an easily obtainable, inexpensive material with high hydrogen content that effectively shields neutrons, but its low density provides limited attenuation of gamma rays and is best used in combination with high-density shielding materials for mobile hot cell applications. Lead, with a density of 11.3 g/cm^3, is a high-density material that effectively shields gamma rays but offers poor neutron attenuation, and its substantial mass can complicate mobile hot cell assembly and transport. Iron and stainless steel feature high density and excellent mechanical properties, finding extensive application in both hot cell and reactor design; the mobile shielded inspection hot cell designed by the China Nuclear Power Technology Research Institute employs cast iron shielding modules [3]. Sand is primarily used as a shielding material in mobile hot cells for radioactive source conditioning, offering advantages of low cost, easy availability, and convenient installation and recovery. The shielding effectiveness varies with sand type and particle size, with Shen Fu et al. [4] demonstrating that higher-density sand provides better shielding and that saturated sand offers stronger attenuation than dry sand.

Composite materials manufactured by mixing multiple components also see widespread application in radiation shielding. Boron steel is frequently used for spent fuel storage, providing combined neutron and gamma shielding capabilities, though boron' s extremely low solubility in steel and the detrimental effects of high boron content on ductility and other mechanical properties limit its application. Lead-boron polyethylene composites offer low density and strong comprehensive shielding performance, effectively reducing shielding weight, but suffer from insufficient structural strength and poor corrosion and radiation resistance. Epoxy resin is a widely used polymer radiation shielding material and a current research focus both domestically and internationally; its shielding capability and mechanical strength can be enhanced by incorporating boron, lead, glass fiber, and other components. Other materials such as nanomaterials and rare earth elements represent important future research directions [17].

Hot cell viewing windows are typically categorized as solid, liquid, or solid-liquid hybrid. Solid viewing windows generally consist of multiple lead glass assemblies coated with anti-reflective layers and are widely used in fixed hot cells due to their reliability. Liquid viewing windows fill the space between hot and cold face glasses with radiation-resistant liquid, typically zinc bromide ($ZnBr_2$) solution. Their advantages in replacement, recovery, and transport make them the most common choice for mobile hot cells. Muhammad, Hannan Bahrin et al. [6] characterized $ZnBr_2$ solution as a liquid radiation shield, obtaining linear attenuation coefficients for solutions of different densities. Table 2 presents the linear attenuation coefficients for various $ZnBr_2$ solution concentrations and water. Using a 1000 Ci 137Cs source, measurements of dose rates on the cold side of mobile hot cells equipped with different solution viewing windows yielded the results shown in Table 3 .

Table 3 demonstrates that water as a shielding material significantly reduces dose rates compared to no shielding (air), while $ZnBr_2$ solution at 1.6 g/cm^3 density further reduces the dose rate by 357 times compared to water, confirming $ZnBr_2$ solution as an excellent viewing window shielding material. It should be noted that $ZnBr_2$ solution viewing window tanks should avoid ferrous metal materials, as contact causes the solution to become turbid and impair visibility. Solid-liquid hybrid viewing windows use high-density glass as the main body with thinner glass sections than solid windows, with oil filling the gaps between glass layers, making them suitable for shielding mixed neutron and gamma radiation sources.

2.2 Manipulators

Manipulators typically consist of a master arm (active side) and slave arm (passive side) connected through a wall penetration component. The master arm is installed on the cold side in the operator area, while the slave arm is installed on the hot side inside the cell. This design ensures operators can manipulate objects within the hot cell from a safe area. Depending on operational requirements, manipulators must possess sufficient degrees of freedom to complete various tasks—for example, seven degrees of freedom enable complex spatial movements. The end-effector, which directly contacts the manipulated object, should be designed according to specific tasks; for grasping and handling operations, it must have appropriate shape, size, and gripping force. Relevant standards for manipulators include EJ/T 566-91 "General Technical Requirements for Master-Slave Manipulators." A schematic diagram of a manipulator structure is shown in Figure 3 [Figure 3: see original paper].

2.3 Transfer Containers

The transfer port of a mobile hot cell is used to receive radioactive materials into the cell interior, with its characteristics and dimensions designed according to experimental requirements. The design must accommodate the shape and size of samples to be transferred while ensuring matching design between the transfer container and port to guarantee sealing and safety during docking. Fixed rails and supports can be used to carry transfer containers and ensure docking precision, while also providing the container body with adequate risk resistance capability. To ensure containers can withstand impacts and drops without damage or radioactive leakage, they typically employ multi-layer structures. Both the container and hot cell feature lid or valve designs to prevent direct contact between the hot and cold sides, as illustrated in Figure 4 [Figure 4: see original paper].

Containers for waste radioactive source conditioning hot cells are designed primarily for long-term storage, consolidating multiple individually stored sources for centralized storage and management at specific locations. Consequently, these containers must be capable of long-distance transport and their materials must withstand prolonged radiation exposure. The UK RWE NUKEM Long-Term Storage Shield (LTSS) [9], for example, features four compartments for source storage with a maximum designed capacity of 10 kCi [9]. In contrast, transfer containers for post-irradiation examination mobile hot cells generally do not require long-distance transport but demand higher sealing standards due to the alpha radioactivity of nuclear fuel. The modular fuel rod transfer device designed by the China Nuclear Power Technology Research Institute for use with its mobile shielded inspection hot cell employs lead as the primary shielding material for gamma attenuation, utilizes a through-design with end caps at both ends, and incorporates an interlock mechanism to connect with the hot cell transfer port, ensuring the container lid can only be opened after tight docking. The opening employs a Z-shaped structural design for shielding, and since fuel rods are extracted from water pools into the container, a drainage channel is also designed to remove water from the cylinder.

3 Future Prospects

As a specialized radioactive protection facility, mobile hot cells possess broad development prospects. With increasing global demand for clean energy, nuclear power is receiving growing attention as an efficient, low-carbon energy source. Many countries are actively advancing nuclear power plant construction and development, which will drive the growth of related industries, including the research, production, and application of mobile hot cells.

3.1 Lightweight

The continuous emergence of novel radiation protection materials will provide strong support for mobile hot cell performance improvements. High-performance composite materials, for instance, offer advantages of light weight, high strength, and effective radiation shielding, and can be used to manufacture hot cell walls and shielding doors to reduce overall weight and enhance mobility and flexibility. Li Honghui et al. [14] developed a vehicle-mounted low-activity waste radioactive source conditioning device employing a container-type sealed structure that significantly reduced overall weight and improved rapid transport capability, while equipped conditioning equipment and auxiliary systems ensured safe and controllable radioactive material operations.

3.2 Intelligent

With the continuous development of artificial intelligence, Internet of Things, and other technologies, the intelligence level of mobile hot cells will progressively improve. Establishing digital twin models for hot cells and mobile hot cells represents a current research hotspot [24]. Intelligent digital twin control systems can achieve real-time monitoring and regulation of the hot cell environment, including precise control of temperature, humidity, radiation dose, and other parameters. Furthermore, future mobile hot cells will be more extensively equipped with advanced remote monitoring systems and user interfaces, enabling operators to monitor various parameters and exercise precise control from greater safe distances via mobile phones, computers, and other terminal devices. This not only enhances operational convenience but also minimizes operator exposure time in radiation environments, safeguarding personnel health.

Zheng Tianyu [26] proposed constructing a hot cell digital twin system that builds a virtual reality simulation model in cyberspace, allowing operators to observe hot cell information from multiple perspectives and angles. Based on 6-DoF pose information, the integration of object detection algorithms such as Yolo and RCNN with path planning algorithms enables collision detection and motion path planning for robotic arms, providing operators with precise operational guidance for more efficient and accurate manipulator movements. Guo Peng [27] designed a virtual reality (VR) simulation system based on Unity3D software that achieves real-time reconstruction of critical hot cell environment elements in a VR simulation environment. As technology advances, the integration of virtual and real elements in digital twin technology will become more sophisticated, representing an important pathway for future intelligent and visualized mobile hot cells and offering new solutions to current challenges such as low operation precision and observation difficulties.

3.3 Modularization

Future mobile hot cells will place greater emphasis on modular design and integrated technology applications. Through standardized design and manufacturing of various functional modules, rapid assembly and disassembly according to different user requirements can be achieved, enhancing versatility and scalability. Concurrently, integrated technology can consolidate multiple devices and systems onto a single platform, reducing hot cell volume and weight while improving overall performance and reliability. To enhance mobility and flexibility, structural design will increasingly trend toward compactness and lightweight construction. By optimizing internal layouts, adopting advanced manufacturing processes, and utilizing lightweight yet high-strength materials, hot cell volume and weight can be reduced, facilitating transport, installation, and relocation to expand application scope.

Modular design enables mobile hot cells to address diverse working condition requirements, encompassing both component-level modularity and overall system modularity. Traditional hot cells are often zoned by function, with each cell dedicated to a single task such as non-destructive testing or metallographic sample preparation. Constrained by space, mobile hot cells must be designed with different functional modules to accommodate various inspection tasks, allowing equipment modules to be swapped based on specific requirements. For scenarios requiring multiple hot cells, mobile hot cells should enable interconnection of two or more units, necessitating standardized interface design and dedicated connection channels for series operation.

3.4 Standardization

As mobile hot cell applications continue to increase, the establishment and improvement of industry standards will become inevitable. Unified industry standards will help regulate interface design, enhance product quality and safety, and promote healthy development of the mobile hot cell industry. Currently, some international standards and specifications exist regarding mobile hot cell design, manufacturing, operation, and maintenance, but further refinement and elaboration are needed. Future standards will continue to evolve and upgrade alongside technological advances and changing application requirements.

4 Summary

In recent years, continuous global research progress has advanced mobile hot cell-related technologies. Mobile hot cell structural designs vary according to functional requirements, and future research will importantly focus on balancing the relationships among shielding capability, lightweight design, and material longevity. Targeted modifications to critical components such as viewing windows, manipulators, and transfer containers will drive mobile hot cells toward lightweight, modular, standardized, and intelligent development.

This paper has analyzed the research and development status of existing mobile hot cell facilities domestically and internationally. As a sophisticated nuclear technology equipment involving multiple cutting-edge disciplines, mobile hot cells are attracting increasing attention from research institutions worldwide. Current development trends both domestically and internationally are advancing toward modularity, intelligence, and enhanced safety, with China making significant progress in modular nuclear technology and digital applications while international experience emphasizes advanced processing technology and standardized collaboration. Future efforts must further overcome key technologies such as lightweight shielding design and multi-functional processing unit integration while promoting standard formulation to expand application scope.

In summary, mobile hot cells hold an irreplaceable position in the nuclear field, providing critical support for safe radioactive material operations, nuclear fuel cycle applications, and research and experimentation. With continuous technological innovation and expanding applications, mobile hot cells will play an increasingly important role in the future nuclear industry.

5 References

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