INL/CON-21-64873-Revision-0

Mobile Hot Cell Digital Twin: End-of-life Management of Disused High Activity Radioactive Sources 23598

February 2023

Changing the World's Energy Future

Rajiv Khadka, John A Koudelka, Kevin L Kenney, Steven E Egan, Bryce C Hillman, Ted R Reed, Blesson Isaac, Konner M Casanova, Gary Alan Newman

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/CON-21-64873-Revision-0

Mobile Hot Cell Digital Twin: End-of-life Management of Disused High Activity Radioactive Sources 23598

Rajiv Khadka, John A Koudelka, Kevin L Kenney, Steven E Egan, Bryce C Hillman, Ted R Reed, Blesson Isaac, Konner M Casanova, Gary Alan Newman

February 2023

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Mobile Hot Cell Digital Twin: End-of-life Management of Disused High Activity Radioactive Sources – 23598

Rajiv Khadka* **, John Koudelka* **, Kevin Kenney*, Eric Egan*, Konner Casanova*, Bryce Hillman*, Ted Reed*, Gary Newman*, and Blesson Issac*

* Idaho National Laboratory, Idaho Falls, Idaho, 83415
**Center for Advanced Energy Studies, Idaho Falls, Idaho, 83401

ABSTRACT

Sealed radioactive sources are utilized for a wide range of applications across nuclear facilities, universities, hospitals, and industry. When these sources reach the end of serviceable life, they become waste. As waste, this radioactive material then goes through a process of recapture and then transfer to long term storage. With the advancement of technology in conjunction with better accessibility of technology, industries are exploring the use of digital automation to enhance productivity, efficiency, and safety while minimizing operation and maintenance costs, health and environmental risks, and uncertainty in the project life cycles. One area for exploration is the use of a digital twin to help design a robust, versatile, and safe solution for recapturing spent sources. We believe this avenue can also provide further advantages in the operations aspect of end-of-life management of spent radioactive sources by reducing the deployment time, increasing operator safety, and reducing operation & maintenance cost. We present a novel digital twin framework for end-of-life management of disused high activity radioactive sources. We have designed and developed a framework that houses a digital twin for visualizing and monitoring the recapture process to inform the engineering and design of a new Mobile Hot Cell. Furthermore, we demonstrate the feasibility of the proposed framework by providing a prototypical implementation, supporting the Mobile Hot Cell and human-machine interface's virtual replication.

INTRODUCTION

In the current era, there are increasing demands and unique challenges for model integration, testing, and validation due to the increasing complexity and integration of engineering designs and complex systems [1]. These engineering designs and structures are increasingly becoming complex because they contain a considerable number of diverse schemes, relationships, dependencies, and a high degree of dynamic behavior [2]. Furthermore, due to the nature of complex systems, even small defects and flaws can cause significant consequences and failure of the entire system.

The nuclear industry, which also involves the use of highly radioactive sources, is one of the examples of an industry involved with complex systems. These highly radioactive sources need to be monitored, maintained, and managed over their lifespan because it is a significant issue for the nuclear industry's sustainable development, environmental protection, and human safety. Proper management of highly radioactive sources once they reach their serviceable life is still a global problem. Additionally, the recovery and consolidation of excess, unwanted, or orphaned high activity sources is also a significant challenge. The Mobile Hot Cell (MHC) has been designed and developed specifically for end-of-life management of disused high-activity radioactive sources [3]. However, there are only a few field-tested MHCs. This MHC construction is time-intensive and can take up to two weeks for assembly and disassembly. Furthermore, during the MHC operations, a problem during processing poses a risk of radiation exposure. Mitigation of such a scenario requires a methodical process that is intense in labor and requires specific resources.

A digital twin provides a reliable and promising approach to reduce the risk and financial cost of designing and constructing a mobile hot cell. It builds a seamless integration and connection between the physical and digital world by providing a computer-simulated representation of the physical world and objects [4]. It allows rapid analysis, experimentation, and real-time decisions to support decision making and analysis [5]. A digital twin framework has the potential to give real-time status on the MHC operations and performance. There is tremendous capability that a digital twin can provide MHC developers and operators, such as the ability to predict issues, simulate dose rate, and understand equipment limitations. It can assist in providing increased connectivity and feedback amongst the engineers to improve the design. It also can provide greater accuracy of the MHC operation needed for performance and prediction analysis. A digital twin can also be used for MHC in creating a development environment to train operators with realistic scenarios, which has the potential to be a hugely valuable asset.

To tackle this problem, this paper presents a framework that visualizes and monitors the entire steps and radiation emission while calculating each timestamp's dose rate during the processing of spent radioactive sources in MHC. Our solution extends the fundamental concept of a digital twin and assures building a reference framework as a solution for mirroring the entities of an MHC in the virtual space. The information obtained from the digital twin framework can offer several optimization opportunities for MHC. Our solution outlines and describes the principal building blocks of the framework and its properties in structure and interrelations. This framework could enable operators to monitor the operations, test changes in an immersive virtual environment. This framework proposes to increase the safety, productivity, and decrease the costs and time for planning and understanding the dose rate accumulation of the radioactive sources.

The novel contributions of this paper can be summarized as follows:

- We propose a digital twin framework for end-of-life management of disused high activity radioactive sources.
- We demonstrate the feasibility of the proposed framework by providing a prototypical implementation, supporting the Mobile Hot Cell and human-machine interface's virtual replication.
- We show how our framework uses immersive virtual environment capabilities combined with a digital twin to monitor and visualize Mobile Hot Cell operations.

BACKGROUND

Digital twin is one of the emerging and most promising technologies in this modern world. A digital twin is a virtual representation of physical equipment that simulates internal processes, mechanical properties, and actions of a real entity while being influenced by intervention and the environment [6]. It is a link between the physical world/entity and the digital space. It also provides the user with information about the current status and future behavior of the physical devices. It also supports testing multiple experimental scenarios to predict future outcomes for risk analysis and decision support. Furthermore, use of a digital twin has several different advantages: physics-based modeling, software integration, verification and validation, visualization, risk analysis, and decision support system. There are a growing use and acceptance of the digital twin capability across various sectors for several diverse use cases [7]. Digital twins have been used to support the nuclear management of a facility undergoing decommission using a web-based platform. Krukovskyi et al., 2020 used digital twin as a tool for the CFD model to monitor and visualize the radiation state of safe confinement of the Chernobyl NPP [8]. Researchers developed a digital twin for gamma background radiation with machine learning algorithms to detect weak and irregular problems [9].

Radioactive waste is generated from various uses, including hospital, academic and commercial testing, the industrial use of radioisotopes, the processing of spent nuclear fuels, and other areas. These radioactive wastes can be in different forms: solid, liquid, gas, or sealed sources. Radioactive waste in sealed sources is enclosed in a small, metallic vessel and can last for several years. The use of sealed radioactive sources is standard, with sources of various types and activities being used for a wide variety of applications. Such sources range from very low activities for sources like reference sources to high active sources like Spent High Activity Radioactive Sources (SHARS) [10]. These sealed radioactive sources still pose health hazards even though the devices containing these sources are not functioning. The International Atomic Energy Association (IAEA) has categorized these sealed sources based on their application, impact on people and the environment, and radioactivity. Categories 1 and 2 pose high risks to human health, and Categories 3, 4, and 5 pose a lower risk. Due to the diverse risks involved, it is critical to handle sealed radioactive sources properly, and proper management of sealed sources is increasingly becoming a global problem [11]. IAEA has described one of the processes for managing radioactive waste as developing a suitable waste package for safe processing, storage, transport, and disposal. Therefore, the development of technology and infrastructure to develop the radioactive waste package for safe disposal is critical for the people and the environment.

One of IAEA's ideas involves using the mobile system for the conditioning and proper management of the highly radioactive sources. The mobile device concept consists of a mobile hot cell (MHC) and a storage container for retrieving, conditioning, and packing highly radioactive sources. This MHC is designed to handle and manage used sealed sources of highly radioactive sources, such as irradiators and teletherapy heads. MHC provides a method to isolate the radioactive materials, thus protecting the operator against dangerous radiation. The isolation of the radioactive materials using the MHC is performed by holding the material in a shielded enclosure in the form of a hot cell. This shielded enclosure is implemented with various manipulation objects (such as robotic arm, milling machine, welding object) to assist the operators in performing the necessary operation without being subject to radiation beyond the allowable dose rate (See Fig. 2). Therefore, to design a hot cell, several requirements to ensure safe and reliable recapture of spent sources.

This novel digital twin framework provides a unique opportunity to visualize, monitor, test, and simulate the end-of-life management of disused high activity radioactive sources using MHC. It allows testing and simulating various radioactive sources and map their radiation. It also supports visualizing the mechanical operation inside the MHC and the accumulation of radiation dose rate during the radioactive source's management. Furthermore, it also provides a user interface that allows the operators/researcher to play and pause the process's simulation.

DESCRIPTION

Concept of Mobile Hot Cell Digital Twin

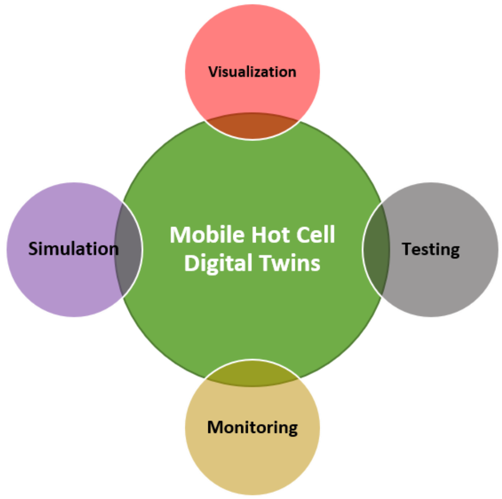

Fig. 1: Conceptual Diagram of MHC digital twin

With the development of computing power and sophisticated software, it is easier to perform scientific simulations and modeling with diverse experimental conditions that incorporate physical models, sensor data, environmental settings, and operational history. In the case of managing highly radioactive sources, parameter data from radiation dose rate accumulation, physical models can be fed back to digital models in real-time via sensors, enabling simulation verification and dynamic adjustment to be completed promptly. By integrating a digital twin into the management of highly radioactive sources, it would be possible to monitor the radioactive exposure rate accumulation and anticipate physical equipment failures in real-time.

MHC Digital Twin (MHC DT) is a novel radioactive simulation that uses digital twin technology with multi-physics, multi-model, and multi-science to provide quick, reliable, and efficient management of disused high activity radioactive sources. MHC DT primarily consists of physical objects, virtual (digital) objects, and radioactive source dose rate data. The physical objects are comprised of a robotic arm, welding components, and unit objects to support the efficient functioning of the radioactive source's physical management. The virtual object is the three-dimensional model of the physical objects, environmental conditions, and the digital system model. The radioactive source dose rate data includes the timestamp of robotic arm movement and dose rate aggregation.

The operation mechanism of MHC DT consists of four mainstages:

1. The replica of the physical models and assets in the digital twin environment using 3D modeling techniques such as SolidWorks, Blender, FreeCAD, and Unity3D.
2. The data connection between the physical and digital environment to monitor and accurately measure the dose rate accumulation throughout the end-of-life management of radioactive sources.
3. The validation of the radiation dose rate accumulation and component functions using the MCNP software.
4. Depending upon the requirement and actual conditions, the continuous development, optimization, and iteration of the MHC DT models and simulation meet and monitor diverse experimental conditions.

MHC DT can play three specific roles in the management of highly radioactive sources: radiation monitoring and measurement, robotic operations, and experimental conditions. MHC DT's use supports the experimenting potential situations in a virtual environment before scheduling and implementing actual changes such as diverse radioactive sources, robotic movements, and virtual radiation experiments. MHC DT allows the researchers and operators to simulate various experimental scenarios, calculate and monitor radiation dose rate accumulation. Without the MHC DT, the researcher and operators can only rely on their domain knowledge and calculation to plan new radiation sources and conditions to see their impact. With the MHC DT, problems and risks involved due to the radiation accumulation can be predicted before they occur in the real physical environment, such as survivability of the components or electronics.

Implementation of MHC DT

Fig. 2 shows the main system components of the MHC DT, and it is composed of physical objects/models, digital objects, radiation modeling, and visualization. The major driving forces of the device is the radiation dose data and visualization. The interaction component in the digital environment will help the users play and pause the robotic arm movement to monitor the task performed and monitor the radiation dose rate accumulation. Physical object data, digital object modeling and simulation, radiation model data, and interaction are internal driving forces of the system. MHC DT supports monitoring and analyzing the radiation dose rate accumulation, environmental data, robotic arm movement, other data from the physical objects, model data, simulation data, evaluation data, and interaction data.

Physical Object

The physical object consists of the mobile hot cell structure, radioactive sources, an electronically controlled robot, shielding blocks, and welding components. All these physical units are interconnected and interact to dispose radioactive sources reliably and safely. Mobile Hot Cell is a compartment that covers the radioactive sources to limit the emission of radiation in the external environment. The radiation dose rate accumulation of the radioactive sources can be measured based on the operational history. Data from the radioactive sources and unit components are calculated and accumulated from the physical units that is then conveyed to the digital space. The physical space data will serve as a prototype to build the digital space of the MHC for visualization and monitoring.

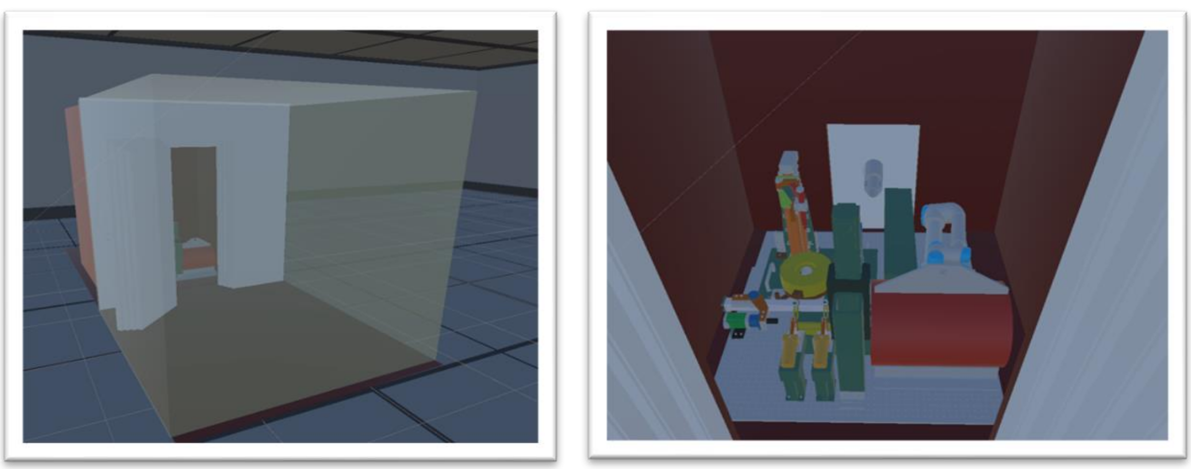

Fig. 2. (Left) Exterior view of digital Mobile Hot Cell (Right) Interior view of digital Mobile Hot Cell with components

Digital Object

The modeling process of the digital environment and objects is shown in Fig. 3. This modeling process aims to monitor the end-of-life management of highly radioactive sources inside the mobile hot cell and provide radiation risks warning to the researchers and operators. The digital environment is built to provide a replica of the real physical environment and objects. The 3D models of the physical objects are developed using Solidworks, Blender, FreeCad, and Unity3D. Then, the robotic arm movements are built to simulate the real world to demonstrate the steps involved in processing the radioactive sources. Finally, the user interaction techniques are integrated to support the interaction with the digital environment and models.

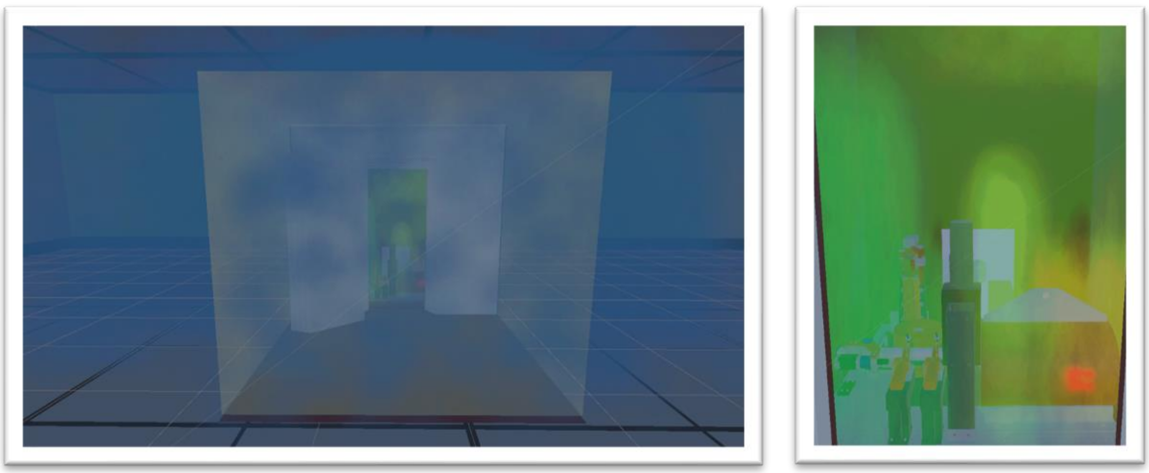

Fig. 3. (Left) Exterior view of Mobile Hot Cell with Radiation Dose Visualization (Right) Interior view of Mobile Hot Cell Components with Radiation Dose Visualization

Radiation Modeling

This framework's primary goal is to support monitoring and analysis of the radiation dose rate accumulation overtime during the management of the radioactive sources. The radiation modeling has been implemented using the Unity3D software. Virtual cloud has been used to model and simulate the radiation exposure depending upon the radioactive source's location using data from MCNP model runs. The virtual cloud is color-coded to represent the intensity of the radiation from the radioactive sources. The radioactive sources continuously emit radiation; therefore, during the entire process of managing the radioactive sources, the radiation dose rate is accumulated and is displayed in the digital environment. The digital environment also shows the total radiation accumulation throughout the management of the radioactive sources. This total radiation will assist the researchers and operators in analyzing and monitoring the risks involved.

Visualization

Visualization is an essential component for digital twin. MHC DT can be visualized in diverse environments ranging from 2D to 3D. This framework has been designed to support several visualization platforms (CAVE, Virtual Reality Head Mounted Display, and Laptops/Desktops) such that the users are not dependent on a specific hardware platform for visualization. The ability to visualize in a three-dimensional environment will allow the user to immerse themselves and navigate to the specific location of the operation and visualize it in depth. Unity3D has been used to develop the framework using the C# programming language.

CONCLUSIONS

The use of MHC DT will support rapid prototyping for building mobile hot cell, prediction of radiation dose rate accumulation, and demonstration of operation. We demonstrated the use of digital twin for end-of-life management of disused high activity radioactive sources and how the framework has been used for interaction and visualizing the mobile hot cell operations for increased reliability and safety.

REFERENCES

1. Madni, A. M., & Sievers, M. (2014). Systems integration: Key perspectives, experiences, and challenges. Systems Engineering, 17(1), 37-51.
2. ElMaraghy, W., ElMaraghy, H., Tomiyama, T., & Monostori, L. (2012). Complexity in engineering design and manufacturing. CIRP annals, 61(2), 793-814.
3. Liebenberg, G. R., & Al-Mughrabi, M. (2008). The development of a mobile hot cell facility for the conditioning of spent high activity radioactive sources (SHARS).
4. Tao, F., Zhang, H., Liu, A., & Nee, A. Y. (2018). Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4), 2405-2415.
5. Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: Values, challenges and enablers from a modeling perspective. Ieee Access, 8, 21980-22012.
6. Boschert, S., & Rosen, R. (2016). Digital twin—the simulation aspect. In Mechatronic futures (pp. 59-74). Springer, Cham.
7. Madni, A. M., Madni, C. C., & Lucero, S. D. (2019). Leveraging digital twin technology in model-based systems engineering. Systems, 7(1), 7.
8. Krukovskyi, P. G., Diadiushko, Y. V., Garin, V. O., Tryfonov, O. V., & Kabanov, Y. (2020). CFD model as a digital twin of the radiation state of the new safe confinement of the Chernobyl NPP. PAST, 128(4), 54-62.
9. Herrera, A., Moore, E. F., & Heifetz, A. (2020). Development of Gamma Background Radiation digital twin with Machine Learning Algorithms: Application of Unsupervised Machine Learning to Detection of Anomalies and Nuisances in Gamma Background Radiation Environmental Screening Data (No. ANL/NSE-20/64). Argonne National Lab.(ANL), Argonne, IL (United States).
10. Liebenberg, G. R., & Al-Mughrabi, M. (2008). The development of a mobile hot cell facility for the conditioning of spent high activity radioactive sources (SHARS).
11. International Atomic Energy Agency. 2003. Categorization of Radioactive Sources. IAEA safety standards series. Vienna, Austria.