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Enhancing Safety in the Construction of Small Modular Reactors (SMRs) and Microreactors (MRs) through Improving Guidelines and Involving Digital Technology Tools

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Abstract: The construction phase of nuclear construction projects presents various risks and hazards, putting workers in potentially dangerous situations. Safety guidelines provided by Occupational Health and Safety Administration (OSHA) aim to address construction safety concerns, but limitations persist, especially in the context of workers safety and the transportation of Small Modular Reactors (SMRs) and Micro Reactors (MRs) in the nuclear construction domain. This research focuses on identifying issues related to safety guidelines in nuclear construction and aims to develop new guidelines and strengthen existing ones. Through a critical literature review, key factors influencing safety in nuclear construction were identified. A questionnaire survey was prepared in line with those identified key safety factors and distributed among 40 professionals from the United States to gather feedback on these factors in countering safety issues and developing new guidelines in the context of nuclear construction. The findings reveal a lack of specific guidelines concerning the safe transportation of SMRs and MRs, as well as a gap in understanding accidents during the construction and transportation phases of nuclear projects. The results of this research contribute to enhancing safety protocols and addressing the unique challenges faced in nuclear construction. The research has also highlighted the importance of digital technology tools such as Artificial Intelligence (AI), Augmented Reality (AR), Virtual Reality (VR), and Unmanned Aerial Vehicles (UAVs) as emerging digital tools, which could be helpful to counter safety concerns linked to SMRs and MRs in future.

Keywords: Nuclear construction, safety guidelines, MRs, SMRs, workers, OSHA guidelines

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1. Introduction

Nuclear construction is one of the most hazardous industries in the world (Wealer et al. 2019). Nuclear safety is a complex, multifaceted system combination of several factors. Budnitz, Rogner, and Shihab-Eldin (2018) have discussed and highlighted various aspects involved in nuclear construction safety. This includes functional, regulatory, socio-political, and economic aspects such as plant design, manufacturing, construction, operation, political and civil society acceptance, public tolerance, etc. To prevent catastrophic accidents, a comprehensive nuclear safety culture should encompass all relevant aspects as a unified and integral entity. Small Modular Reactors (SMRs) are advanced nuclear reactors with a capacity to produce electricity up to 300 MW(e) (Hidayatullah, 2015). The components and systems of SMR can be factory-built and then transported or shipped as modules to sites for installation with respect to demand (IAEA, 2016; IAEA, 2011). Similarly, Microreactors (MRs) are compact nuclear reactors that produce up to 20 MW(e) or less of electrical power. They are designed to be modular and portable, with the ability to be factory-built and easily transported. Along with the generation of electricity, it can also be independently used and suitable for heat generation for industrial facilities (Testoni et al., 2021). Some researchers, such as Black, Shropshire, Araújo, and van Heek (2022), believe that the MRs can produce energy up to 50MW(e). MRs can be transported using different modes of transport, such as highway, rail, barge/ship, or even cargo airlift (Testoni et al., 2021). There are almost 50 types of MRs across the world that are in the manufacturing stage now (IAEA ARIS, 2023). However, the real problem linked with the supply of these reactors in bulk quantity is not validated and investigated due to a lack of data in the literature on past accidents in the construction and transportation phase of nuclear reactors. Currently, there are no proven methods for evaluating the safety of a fully fueled MR module during transportation and mobilization/demobilization at remote locations, as no safety-assessment methodologies or regulatory acceptance criteria have been shown to be adequate for this purpose. The creation of new guidelines for the transportation of fueled reactor modules to and from remote sites poses significant challenges (Testoni et al., 2021).

Along with the safety in transporting and installing SMRs and MRs, the safety of construction workers is equally an important domain in the construction and transportation phase. For workers and the public in case of an accident or impacting the construction site, the licensee is obligated to establish emergency preparedness and response arrangements for sites with pre-existing nuclear facilities (IAEA 2002). However, the biggest hurdle in ensuring and understanding the response of workers and safety staff in the context of accidents on nuclear construction sites is the absence of accidental data, specifically related to nuclear construction. This gap in literature is what the authors aim to address in this research paper. The accident data available in the past literature falls 100% in the Operation Phase (OP) of nuclear reactors. In the context of operational incidents, it is evident that all these accidents stem from human-made hazards, with the majority of these incidents being attributed to the release of radioactive materials. However, Kotani et al (2022) argues that natural hazard leading to accidents in nuclear reactors is seismic activity, particularly earthquakes. Therefore, the percentage of accidents from the past literature shows more weightage to man-made hazards compared to natural hazards, and examples of such incidents are Fukushima in Japan, the Fleurus incident in Belgium, and the Erwin incident in the USA, as discussed by Guardian (2016). This study undertakes a meticulous investigation and critical evaluation of the regulatory guidelines and precautionary measures established by prominent organizations such as the Occupational Health and Safety Administration (OSHA), International Atomic Energy Agency (IAEA), Nuclear Regulatory Commission (NRC), and Department of Energy (DOE). Its primary objective is to analyze their guidelines based on past accidents, aiming to enhance occupational safety and protect workers during the transportation and construction of SMRs and MRs. Through an extensive analysis of historical incidents and their root causes, this study proposes comprehensive recommendations that will enhance the safety of workers in nuclear construction and avoid accidents in OP.

SMRs are being considered as a viable alternative to traditional large nuclear reactors due to their improved safety record, smaller size, lower upfront costs, and better alignment with grid and market (Budnitz et al., 2018; Locatelli, Bingham, & Mancini, 2014). Despite the advancement in nuclear technology in terms of SMRs and MRs the most significant challenge still faced by nuclear power plants and nuclear fuel complexes is the possibility of a catastrophic accident that could result in substantial damage to the facility and significant offsite release of radioactive materials which can cause damage to workers too. To counter such issues Morrow, Koves, and Barnes (2014) have emphasized giving attention to safety cultural issues through high empowerment of regulatory bodies, as the deficiencies in the safety- cultures remain the biggest hurdles and root of safety matters.

In the light of understanding and evidence from the above discussion it is quite evident that past literature truly lacks safety measures, statistical data of accidents and guidelines in the transportation and construction phase of nuclear construction which need to be addressed to achieve safety. Nonetheless, the reports published by INPO (2013) and USNRC (2014) did touch upon certain factors, primarily within the scope of operational procedures (OP). Rutter (2023) argued that establishing a safety culture involves integrating socio-cultural and operational aspects, ensuring organizational alignment with cultural preferences while prioritizing worker safety and fostering transparency through a questioning attitude. Locatelli et al. (2014) have argued the importance of economic viability and safety concerns as the biggest impediments to the installments of SMRs, and these concerns have even gained more momentum following the Fukushima accident in Japan. Huang et al. (2013) also mentioned how the Fukushima accident has changed the perception of the common public to the potential risks linked with nuclear power. Therefore, it is extremely important to sort out issues linked to the safety of nuclear installments on the site. Similarly, Budnitz et al. (2018) reviewed and explained the prospects of nuclear power around the world, and views on various ways to strengthen safety regimes to foster a nuclear safety culture globally. The possible attributes of safety and most specifically social and cultural aspects were discussed to understand how an independent national regulatory authority is essential to achieve and meet safety concerns in this domain. However, apart from emphasizing the importance of a regulatory body, it is equally crucial to establish and regularly update rules, as well as maintain a comprehensive database of historical accident data related to nuclear construction sites, a current deficiency in the system.

Nonetheless, scholarly literature exhibits a deficiency in authentic and comprehensive data pertaining to the types of accidents that occur among workers involved in nuclear construction activities, such as the construction and transportation of SMRs and MRs. This inadequacy hampers a thorough comprehension of the real circumstances encountered on construction sites. Furthermore, existing literature fails to encompass sufficient research studies examining safety concerns during the transportation and construction phase of SMRs and MRs. Consequently, the purpose of this study is to address this research gap by investigating the absence of guidelines and frameworks for evaluating and assessing safety issues during the construction phase of nuclear projects. The Research Questions (RQ) or objectives of the study are as follows:

- RQ1: Assessing existing OSHA safety guidelines for SMRs and MRs in the construction and transportation phase and identifying gaps.

- RQ2: Can the existing guidelines for SMRs and MRs effectively address safety issues and establish a comprehensive framework for construction and transportation activities in nuclear construction?
- RQ3: In the future, how digital technology tools (i.e., Artificial Intelligence (AI), Internet of Things (IoT), Virtual Reality (VR), and Augmented Reality (AR)) could be utilized to enhance the safety of SMRs and MRs in construction and transportation.

2. Research Methodology

The research methodology adopted for this study involved several key steps to ensure a comprehensive investigation. The initial stage involved conducting a thorough literature review, which served as the foundation for the research. The review encompassed a critical analysis of research articles, reports, and other reliable sources to identify key factors and gaps in existing knowledge pertaining to the safety of SMRs and MRs in the construction and transportation phase. Based on the insights gained from the literature review, the next step involved the development of a detailed questionnaire. The questionnaire was carefully crafted to align with the research objectives and address the identified gaps in knowledge. It was designed to gather expert opinions and perspectives on critical factors related to the safety of SMRs and MRs during their construction and transportation phases.

The questionnaire was divided into three sections, corresponding to each RQ. The first section focused on evaluating existing safety guidelines for SMR and MR, examining their strengths, and identifying any shortcomings. The second section aimed to explore potential improvements to these guidelines, considering future safety issues that may arise during the construction and transportation phase. The final section explored the role of digital technology tools, such as AI, IoT, VR, AR, and UAVs in enhancing safety during construction. The questionnaire was distributed to a selected group of participants comprising professionals from academia and research institutes. The participants were chosen based on their in-depth knowledge of SMRs and MRs technologies and their familiarity with nuclear safety and construction. While distributing the questionnaire survey, it was considered strictly that participants must be from the United States of America and have knowledge both on SMRs, MRs, and the construction industry, specifically in the perspective of nuclear construction and transportation processes. Moreover, researchers from the nuclear energy domain were also included in this survey who possess knowledge of the SMRs, MRs, and the implications and processes that exist during the construction and transportation of these tools. The distribution of the questionnaire was done through email, and an 80% response rate was achieved. Following the collection of responses, data analysis was conducted to extract meaningful insights and draw conclusions. The survey data was processed and analyzed using appropriate statistical techniques and quantitative analysis methods. The findings were then discussed in detail, considering the research objectives and the existing literature. Overall, this research methodology encompassed a comprehensive literature review, the development and distribution of a tailored questionnaire, rigorous data analysis, and a thorough discussion of the findings. These steps ensured a systematic and reliable approach to investigating the safety aspects of SMRs and MRs during their construction and transportation phases, contributing to the advancement of knowledge in the field.

2.1. Defining key factors

The deployment and construction of SMRs and MRs pose significant challenges and necessitate robust safety measures. Through an extensive review of literature, the key factors and gaps in existing guidelines related to the safety of SMRs and MRs during transportation and construction phases were identified which are shown in Table 1 below. The importance of addressing the factors listed in Table 1 cannot be understated, as they have been identified as significant contributors to accidents in nuclear power plants. Incidents such as the Fukushima accident in Japan, the Fleurus incident in Belgium, the Erwin incident in the USA, and the Braidwood incident in the USA serve as reminders of the potential risks involved. Therefore, it is crucial to reinforce guidelines and develop comprehensive frameworks to ensure the safe handling of SMRs and MRs during their transportation and construction phases (Nakayoshi et al., 2020).

The literature highlights that the characteristics of SMRs and MRs, including their types and fueling capacities, require careful consideration. Various transportation methods, such as highways, railways, waterborne vessels, and air transport, can be employed to transport SMRs and MRs to their installation points (Testoni et al., 2021). However, the absence of proper guidelines for handling these aspects poses significant risks. The lack of extensive practical experience in managing SMRs and MRs on a large scale, coupled with limited awareness, further emphasizes the need for comprehensive guidelines.

In addition to reinforcing guidelines, on-site training plays a crucial role in ensuring safety during the construction process. Table 1 presents key factors utilized in the construction industry to ensure on-site safety compliance. These factors not only guide workers in adhering to safety protocols but also provide insights into the nature of work and potential threats that may arise during specific activities (Rice 2022; Tool, 2021). Moreover, enhancing safety culture during the construction involves strategies such as adopting technology and promoting knowledge sharing among stakeholders (Golparvar-Fard, Pena-Mora, & Savarese, 2015; Mihic, Vukomanovic, & Završki, 2019). Likewise, Government entities like the NRC and the DOE also play a vital role in fostering a culture of safety. Table 1 provides an overview of the primary factors through which the safety of SMRs and MRs can be improved during the transportation and construction phases. Moreover, some researchers Gambatese, Behm, and Rajendran (2008) and Loosemore and Malouf (2019) have pointed out critical areas beyond on-site training and guidelines to ensure safety. Table 1 presents an overview of significant grey areas and aspects that should be prioritized based on their importance. This comprehensive approach ensures that all potential risks and challenges are identified and effectively managed.

Digital technology tools, as highlighted in Table 1, play a crucial role in the construction industry by offering increased productivity and enhanced safety measures (Getuli, 2020). Advanced technologies such as AI, VR, AR, IoT, drones, and Unmanned Aerial Vehicles (UAVs) have significant potential to improve safety oversight and risk management during the construction phase of SMRs and MRs. For example, AI has been utilized to reduce waste on construction sites, which can contribute to human-induced accidents. By harnessing the power of these digital tools, construction professionals can optimize resource utilization, mitigate potential hazards, and ensure timely and accurate project delivery.

Incorporating digital technology in the construction and transportation phase of SMRs and MRs offers significant potential for improving efficiency, productivity, and safety. The literature highlights the benefits of utilizing advanced technologies such as AI, VR, AR, IoT, drones, and UAVs (Fang, 2020). These technologies can enable better safety oversight, enhance risk management practices, streamline construction processes, and provide real-time monitoring and data analysis capabilities. AI is a potent tool employed by researchers Bang and Andersen (2022) to mitigate waste on construction sites, a factor often contributing significantly to human-induced accidents. Therefore, by harnessing the power of digital tools, construction professionals can optimize resource utilization, mitigate potential hazards, and ensure timely and accurate project delivery. The insights provided by Table 1 serve as a valuable reference for industry stakeholders looking to leverage digital technology advancements to drive improvements in the construction and transportation phase of SMRs and MRs.

In conclusion, Table 1 serves as a valuable point of reference for stakeholders in the industry who aim to enhance safety measures during the construction and transportation phase of SMRs and MRs. Key measures for ensuring the safe and successful implementation of SMRs and MRs in the nuclear construction sector include addressing identified factors, reinforcing guidelines, providing on-site training, adopting digital technology, and cultivating a safety culture. The analysis of existing literature emphasizes the necessity for comprehensive safety guidelines, as well as the integration of digital technology and on-site training to safeguard workers and mitigate potential risks. The findings underscore the significance of strengthening safety culture, complying with regulations, and promoting the use of safety equipment. Additionally, the research sheds light on risks associated with transportation methods, growing community concerns, and the potential for legal action. Identification of these factors and risks lays the groundwork for formulating guidelines, fostering safety culture, and enhancing safety practices in the construction and transportation of SMRs and MRs. Furthermore, exploring innovative technologies such as AI, VR, AR, IoT, drones, and UAVs provides insights into their potential applications for enhancing safety during the construction and transportation phase. A comprehensive understanding of these factors, risks, and technological possibilities will aid the industry in developing effective strategies to ensure the secure deployment and construction of SMRs and MRs, thereby advancing the field of nuclear energy.

Table 1. Critical factors and guidelines for safe handling of SMRs and MRs in transportation and construction phases

Safety concerns of SMRs and MR	Key factors	References
Major causes of accidents	Earthquake	((Nakayoshi et al., 2020)
	Tsunami	(Guardian, 2016)
	Mechanical failure	(Cai, Li, Yin, Zhu, & Zhou, 2020)
	Operator error	
	Management deficiencies	(Christopher et al., 2020)
	Design	(Carlson, Miller, & Wu, 2022)
Construction safety considerations	Skilled workforce	(Durdyev, Mohamed, Lay, & Ismail, 2017)
	Safety equipment utilization	(Leje, Shamsulhadi, Fadhlin, & Muhammad-Jamil, 2020)
	Risk assessment	(Leje et al., 2020)
	Hazard mitigation	(Durdyev et al., 2017)
	Regulatory compliance	(Durdyev et al., 2017; Mak et al., 2019)
Characteristics of SMRs and MRs	Types of SMRs and MRs	(Hussein, 2020; Rowinski, White, & Zhao, 2015),
	Types of MR	(Hussein, 2020; Zeliang, Mi, Tokuhiro, Lu, & Rezvoi, 2020)
	Fueling capacity	
	Type of fuel	(Hussein, 2020; Zohuri, 2020)
	Deployment transportation	(Rowinski et al., 2015)
Major risk factors in construction industry	Construction delays	(Boadu, Wang, & Sunindijo, 2020; Durdyev & Hosseini, 2020)
	Environmental impacts	(Boadu et al., 2020)
	Increasing community concerns	(Durdyev & Hosseini, 2020)
	Budget overrun	(Afzal, Yunfei, Nazir, & Bhatti, 2021; Durdyev & Hosseini, 2020)
	Litigation Risk Amplification	

Table 1. Critical factors and guidelines for safe handling of SMRs and MRs in transportation and construction phases (continued)

Safety concerns of SMRs and MR	Key factors	References
Human induced accidents on nuclear construction sites	Fire and explosions	(Akan & Karaman, 2022; Chan, Baghbaderani, & Sarvari, 2022)
	Contamination	(Chan et al., 2022; Khan, Ali, De Felice, & Petrillo, 2019)
	Falls and failing objects	(Chan et al., 2022; Khan et al., 2019)
	Confined space accidents	
	Transportation-related accidents during the delivery or installation of components	(Kang et al., 2022)
	Chemical hazards	(Chan et al., 2022; Sanni-Anibire, Mahmoud, Hassanain, & Salami, 2020)
	Electrical accidents	
Safety concerns of SMRs and MR	Key factors	References
Major causes of accidents	Earthquake	((Nakayoshi et al., 2020)
	Tsunami	(Guardian, 2016)
	Mechanical failure	(Cai, Li, Yin, Zhu, & Zhou, 2020)
	Operator error	
	Management deficiencies	(Christopher et al., 2020)
	Design	(Carlson, Miller, & Wu, 2022)
Construction safety considerations	Skilled workforce	(Durdyev, Mohamed, Lay, & Ismail, 2017)
	Safety equipment utilization	(Leje, Shamsulhadi, Fadhlin, & Muhammad-Jamil, 2020)
	Risk assessment	(Leje et al., 2020)
	Hazard mitigation	(Durdyev et al., 2017)
	Regulatory compliance	(Durdyev et al., 2017; Mak et al., 2019)
Characteristics of SMRs and MRs	Types of SMRs and MRs	(Hussein, 2020; Rowinski, White, & Zhao, 2015),
	Types of MR	(Hussein, 2020; Zeliang, Mi, Tokuhiro, Lu, & Rezvoi, 2020)
	Fueling capacity	
	Type of fuel	(Hussein, 2020; Zohuri, 2020)
	Deployment transportation	(Rowinski et al., 2015)
Major risk factors in construction industry	Construction delays	(Boadu, Wang, & Sunindijo, 2020; Durdyev & Hosseini, 2020)
	Environmental impacts	(Boadu et al., 2020)
	Increasing community concerns	(Durdyev & Hosseini, 2020)
	Budget overrun	(Afzal, Yunfei, Nazir, & Bhatti, 2021; Durdyev & Hosseini, 2020)
	Litigation Risk Amplification	
Human induced accidents on nuclear construction sites	Fire and explosions	(Akan & Karaman, 2022; Chan, Baghbaderani, & Sarvari, 2022)
	Contamination	(Chan et al., 2022; Khan, Ali, De Felice, & Petrillo, 2019)
	Falls and failing objects	(Chan et al., 2022; Khan et al., 2019)
	Confined space accidents	
	Transportation-related accidents during the delivery or installation of components	(Kang et al., 2022)
	Chemical hazards	(Chan et al., 2022; Sanni-Anibire, Mahmoud, Hassanain, & Salami, 2020)
	Electrical accidents	
Factors for on-site safety compliance	The Center for Construction Research and Training (CPWR) Toolbox talks	(Rice et al., 2022; Tool, 2021)
	Safety regulations	(Rice et al., 2022)
	Equipment handling	(Tool, 2021)

Table 1. Critical factors and guidelines for safe handling of SMRs and MRs in transportation and construction phases (continued)

Venues for improving safety culture in construction	Knowledge sharing	(Golparvar-Fard et al., 2015; Ho & Dzeng, 2010)
	Collaboration	
	Workforce training	(Ho & Dzeng, 2010)
	Innovative endeavors	(Golparvar-Fard et al., 2015; Mihic et al., 2019),
	Technology integration	
	Safety culture enhancement	(Mihic et al., 2019)
Key areas prioritizing safety in construction	Design improvement	(Gambatese et al., 2008)
	Workforce training	(Gambatese et al., 2008; Loosemore & Malouf, 2019)
	Quality Assurance and Quality Control (QA&QC)	
	Improve safety guidelines	(Loosemore & Malouf, 2019)
	Research enhancement	(Gao, Gonzalez, & Yiu, 2019)
Technology tools for enhancing safety in nuclear construction	AI	(Boje, Guerriero, Kubicki, & Rezgui, 2020)
	VR	(Akinosho et al., 2020)
	AR	(Getuli et al., 2020)
	VR	
	IoT	(Boje et al., 2020)
	Drones	(Fang et al., 2020)
	UAVs	(Boje et al., 2020)
Areas of improvement with digital technology utilization	3D models development	(Cheng & Teizer, 2013; Shafiq, Afzal, & Aljassmi, 2021)
	Risk analysis	Bang and Andersen (2022)
	Data-driven site analysis	(Shafiq et al., 2021)
	Real-time supervision	(Xu, Chong, & Liao, 2019; H. Zhang, Yan, Li, Jin, & Fu, 2019)
	Accident-based guidelines	(Forteza, Carretero-Gómez, & Sesé, 2020; Z. Zhang, Li, & Yang, 2021)

3. Data and Analysis

3.1. Questionnaire survey

After identifying key factors, the authors carefully crafted a comprehensive questionnaire aligned with three research objectives (RQs) to gather expert opinions on the safety of SMRs and MRs during construction and transportation. It aligned with three research objectives (RQs). The questionnaire had three sections: one addressing existing safety guidelines for SMRs and MRs (RQ1), the second proposing improvements for future safety concerns (RQ2), and the third examining the role of digital technologies (AI, IoT, VR, AR, UAVs, drones) in enhancing safety. The subsequent sections of the study present survey results (3.2 to 3.5) and provide a summary in section 3.6.

3.2. Causes of accidents in nuclear plants

The survey results revealed valuable insights regarding the main causes of accidents in nuclear power plants. Among the participants, 38% attributed major accidents to design failures, while 26.92% identified management deficiencies as a significant contributing factor. These findings highlight the participants' perceptions regarding the primary causes of accidents in nuclear power plants. Such insights provide a basis for understanding the areas that require attention and improvement to enhance safety measures and mitigate the risk of accidents.

3.3. Factors essential for ensuring safety during transportation of SMRs and MRs

To address RQ1, a series of questions were presented to the participants, focusing on the evaluation of existing safety guidelines provided by OSHA for SMRs and MRs in the construction and transportation phase, as well as identifying any potential gaps. The survey results are shown in Fig. 1, Fig. 2, and Fig. 3 below. The findings presented in Fig. 2 indicate that among the various factors considered for the development of safety regulations for SMRs and MRs during transportation and construction, the means of transport (e.g., trucks, loaders, ships, etc.) holds the greatest significance in strengthening and formulating new rules. The type of MR ranks as the second most important characteristic to be examined when evaluating safety guidelines.

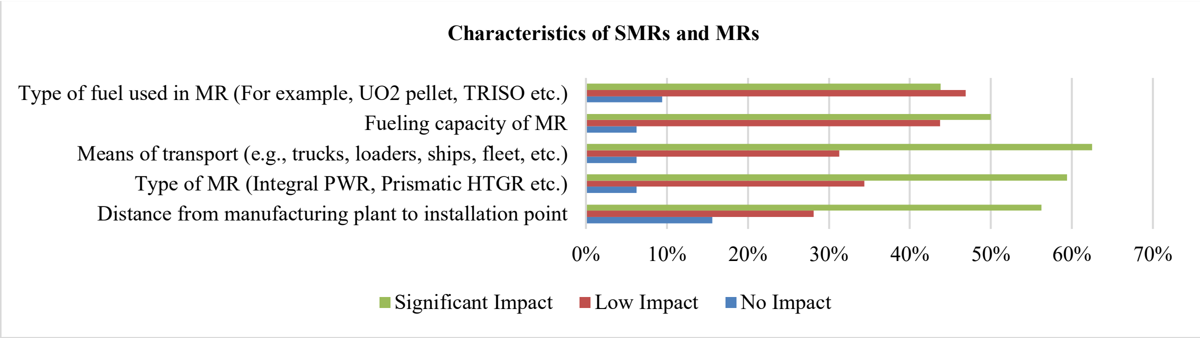

Fig. 1. Importance of features of SMRs and MRs that may be counted in developing new guidelines.

3.3.1. Major Risk Factors Linked to SMRs and MRs

Fig. 3 depicts the probability of various risks during the construction and transportation of SMRs and MRs when adhering to existing guidelines, without the development of novel guidelines that are aligned with the specific demands and characteristics of the work. The findings demonstrate a notable area of concern, as a substantial majority (78.13%) of survey participants emphasized the probability of encountering construction delays, environmental degradation, and community concerns in the absence of well-defined regulations. These risks pose substantial threats to both workers and the surrounding environment, underscoring the importance of considering these aspects when formulating guidelines.

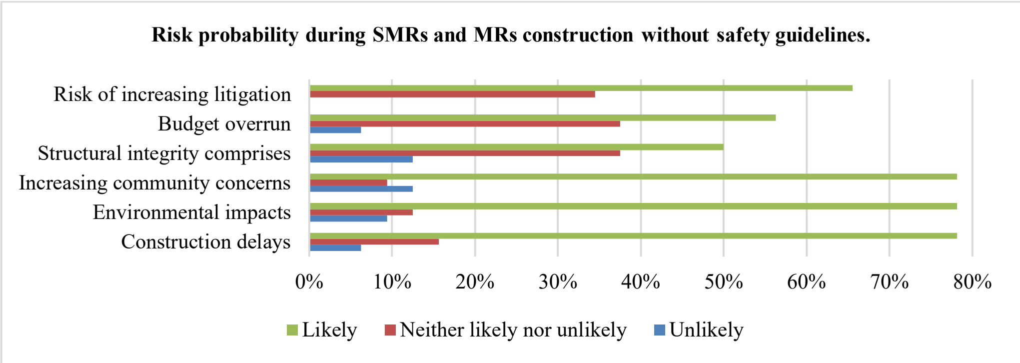

Fig. 2. Risk probability in SMR and MR construction in the absence of safety guidelines.

3.3.2. Human-induced accidents on nuclear construction sites

In nuclear construction, safeguarding personnel and the environment through safety measures is vital. Yet, the novel nature of SMRs and MRs may leave industry stakeholders and workers unfamiliar with their unique requirements. Fig. 4 highlights potential major accidents that can occur without tailored guidelines for these technologies, revealing a significant likelihood of such incidents. Survey respondents emphasized a high probability of accidents during delivery and installation, at 84.38%. This underscores the urgency of developing technology-specific guidelines for transportation in SMRs and MRs.

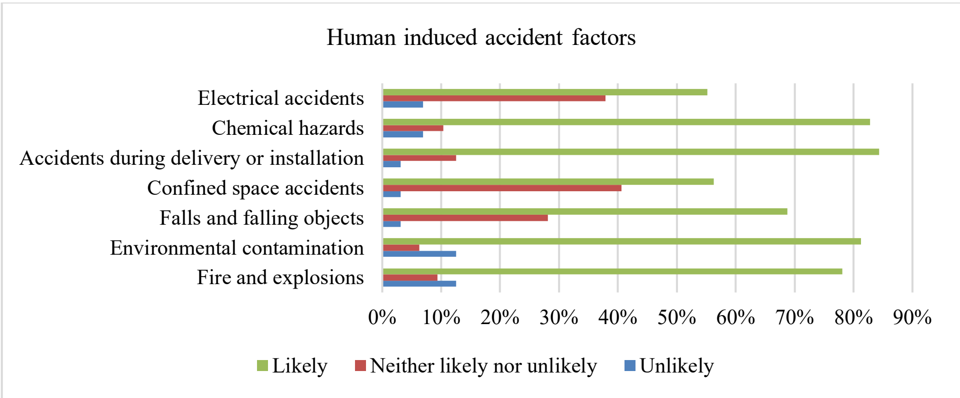

Fig. 3. Human-induced factors that may cause accidents on nuclear construction sites.

3.4. Avenues for Improving Safety Culture in Construction

In pursuit of RQ2, three questions were administered to the participants to examine the adequacy of guidelines for SMRs and MRs in addressing safety concerns during the construction and transportation phase, while also identifying existing gaps. The survey results revealed that approximately 80% of the participants perceived the current guidelines to be fully implemented on construction sites, whereas the remaining 20% expressed concerns about partial adherence. Additionally, Fig. 4 emphasizes essential areas and approaches that contribute to ensuring worker safety during the construction of SMRs and MRs. Each factor depicted in the graph demonstrates an effectiveness level of over 80%, underscoring their significance in formulating and reinforcing safety measures for SMRs and MRs during the construction phase.

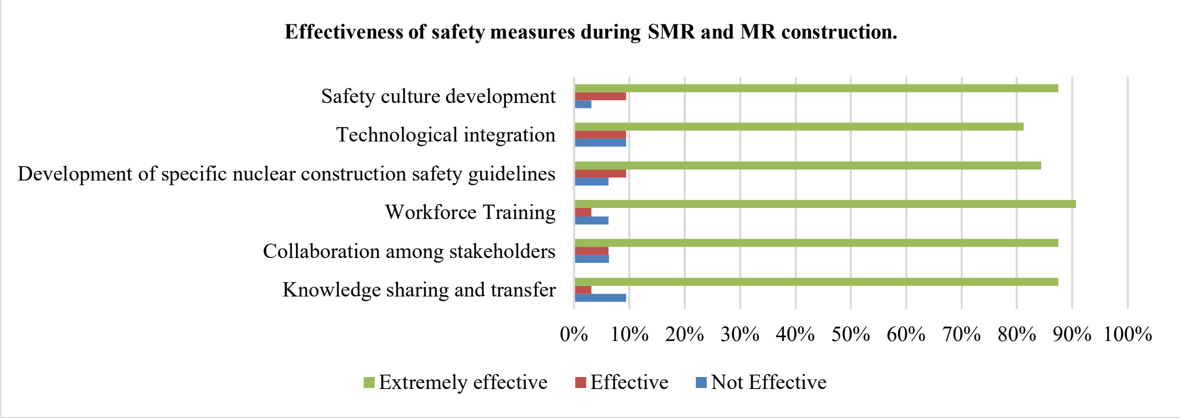

Fig. 4. Importance of safety measures having a huge impact during SMRs and MRs construction

3.4.1. Key areas to enhance the safety of SMRs and MRs

Through a comprehensive literature review, it was discovered that OSHA lacks specific guidelines for handling the activities involved in the construction and transportation phases of SMRs and MRs. Fig. 5 supports this finding by presenting the survey results, which indicate that 90.63% of participants recommended the improvement of safety guidelines in this domain. Additionally, the survey respondents emphasized the importance of enhancing the skills of the workforce in relation to SMRs and MRs construction.

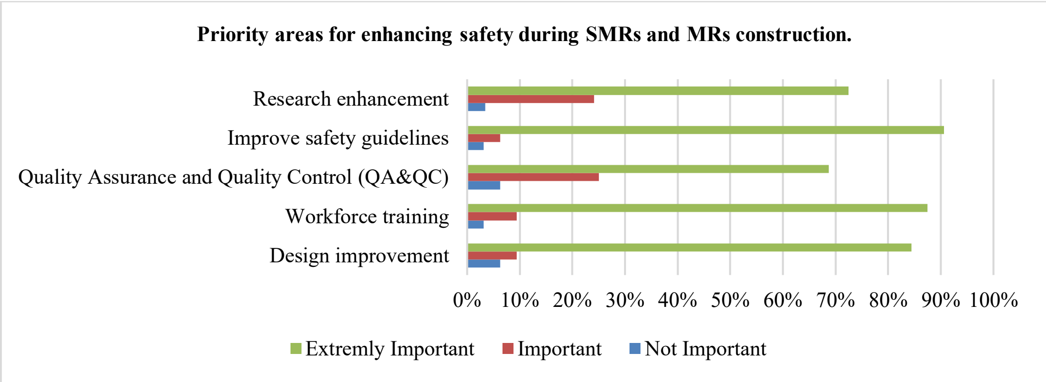

Fig. 5. Possible venues for enhancing safety during SMRs and MRs construction.

3.5. Role of Technology Tools in Enhancing Safety of SMRs and MRs.

To address RQ3, two questions were posed to the participants. These questions aimed to explore the role of digital technology tools such as AI, IoT, VR, and AR, UAVs, drones in improving the safety of SMRs and MRs during the transportation and construction phases. The following Fig. 6 presents the outcomes of the authors' investigation into the potential utilization of various technological tools discussed in the literature to enhance worker safety in the construction industry, specifically in the context of SMRs and MRs during the construction and transportation phases. The results highlight significant potential for the adoption of emerging technologies such as AR, VR, and AI with a weightage of 71.88% each according to the participants. However, the Internet of Things (IoT) received a lower weightage of 46.88% as being considered effective in this regard. Therefore, the development of new guidelines in this regard must be made in line with these technology tools which can bring positive changes in the safety domain during construction and deployment of SMRs and MRs.

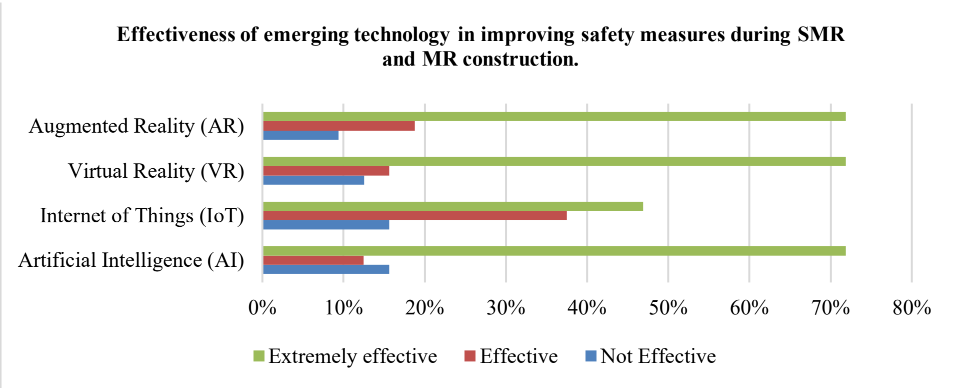

Fig. 6. The role and impact of technological tools in improving safety measures of SMRs and MRs

The question also aimed to assess the potential of UAVs and remote sensing devices in improving safety oversight and risk management during the construction and transportation phase of SMRs and MRs. The objective was to explore how these technological tools could be utilized in the future to enhance worker safety and contribute to the development of new guidelines for the construction and transportation phases. The survey results, as depicted in Fig. 7, highlight a significant opportunity for leveraging UAVs and remote sensing devices in the domain of real-time supervision.

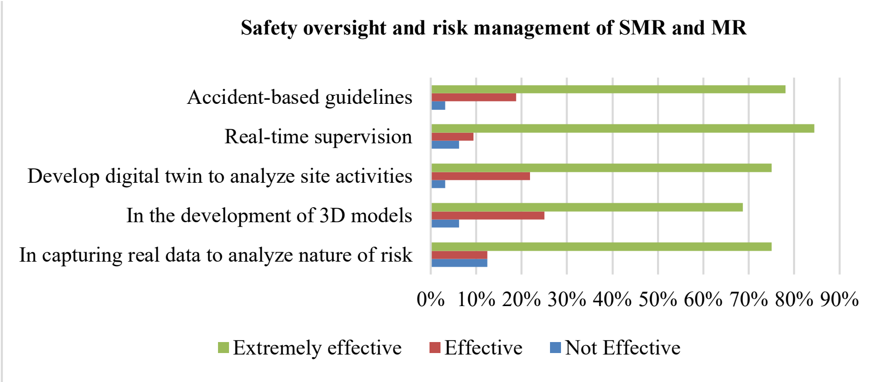

Fig. 7. Role of UAVs and remote sensing devices for safety oversight in the construction of SMRs and MRs

An overwhelming 84.38% of the participants recognized the considerable effectiveness of these tools in facilitating real-time supervision and monitoring of various activities throughout the construction and transportation phase of SMRs and MRs. This finding underscores the importance of utilizing UAVs and remote sensing devices to bridge the existing gap in real-time supervision and enhance safety measures during construction operations.

3.6. Summary

The results of the questionnaire highlight the urgent need for the development of comprehensive guidelines and the adoption of innovative technologies to ensure the safety of SMRs and MRs during their construction and transportation phases. The results emphasize the significance of considering means of transport and formulating specialized safety guidelines to effectively address potential risks. Moreover, the study underlines the probabilities of construction delays, environmental degradation, and community concerns if existing guidelines are not revised to accommodate the unique requirements of SMRs and MRs. The research further demonstrates the immense potential of emerging technologies such as AR, VR, AI, and IoT in enhancing safety measures, however, there is a need to have more research in this domain to have efficient workflows for these emerging technologies. Additionally, the results also highlighted UAVs and remote sensing devices as valuable means of real-time supervision and monitoring during construction activities. The findings of this study provide crucial insights for policymakers, industry professionals, and researchers involved in SMRs and MRs projects, facilitating informed decision-making and the implementation of effective risk mitigation strategies to safeguard the well-being of workers and the environment.

4. Discussion

4.1. Significance of Safety Guidelines for Construction and Transportation of SMRs and MRs

The authors conducted a comprehensive analysis of key factors using a detailed questionnaire survey to enhance safety procedures and protocols for the future implementation of SMRs and MRs. Currently, there is a significant gap in both the availability and understanding of safety measures required for the widespread deployment of SMRs and MRs. The lack of practical experience in deploying and installing a substantial number of SMRs and MRs systems while maintaining an efficient supply chain followed by the security and proliferation risk (Testoni et al., 2021). The absence of a defined methodology for addressing safety concerns during the transportation and construction processes of SMRs and MRs arises from the fact that these technologies have not yet progressed beyond the developmental stage to real-world production and deployment. This gap highlights the need to enhance the existing guidelines provided by OSHA and to foster a stronger safety culture within the relevant entities involved in SMRs and MRs initiatives.

Additionally, the authors' motivation to explore further into the safety during construction and transportation of SMRs and MRs stems from the escalating threats posed by climate change and environmental pollution. These factors have compelled the world to consider nuclear energy as a viable and secure low-carbon alternative (Morgan, Abdulla, Ford, & Rath, 2018) Hence, it is imperative to ensure that the safety aspects of SMRs and MRs are thoroughly addressed and integrated into their lifecycle to meet the growing demand for sustainable energy sources.

4.2. SMRs and MRs Deployment Procedure

The academic literature highlights a significant concern regarding the mass supply of SMRs and MRs, which is likely to emerge as a substantial challenge to the industrial adaptation of these technologies in the future after their manufacturing is done (Cooper, 2014). The precise challenges involved in sustaining the supply chain while ensuring worker safety and the successful deployment of fully built SMRs and MRs systems are difficult to anticipate at this stage. However, by drawing upon insights from past accidents and identifying gaps in OSHA guidance, researchers and technology-adopting agencies can provide valuable predictions and guidance in developing counter strategies for addressing these challenges effectively. In the present circumstances, it is of great importance to assess the sequential stages encompassing the deployment of SMRs and MRs, commencing from their manufacturing facilities to the actual installation sites. This entire process entails numerous interconnected steps, involving both the workforce and machinery. Therefore, it is crucial to establish clear definitions for each activity, aligning them with the guidance provided by OSHA, to prevent any incidents that could potentially jeopardize human lives and the integrity of the SMRs and MRs. The deployment procedure for SMRs and MRs involves several key steps. However, the authors are concerned about the steps that come in the transportation and construction phase which are also discussed by Black et al. (2022) as follows:

Planning and pre-deployment assessment: This phase includes site selection, feasibility studies, and environmental impact assessments to determine the suitability of the location for SMRs or MRs deployment. Regulatory requirements and licensing processes are also assessed during this stage.

Transportation and installation: SMRs and MRs are transported to the installation site using various means, including highway, rail, barge/ship, or air, adhering to transportation regulations and safety protocols. At the installation site, the reactors are assembled, connected to the power grid, and integrated with auxiliary systems.

Decommissioning and waste management: At the end of the operational life, proper decommissioning procedures are followed, including the safe removal and disposal of radioactive materials. Waste management practices are implemented to handle and store radioactive waste generated during the operation and decommissioning phases, adhering to regulatory guidelines. Throughout the deployment procedure, safety measures, regulatory compliance, and stakeholder engagement are paramount to ensure the safe and responsible deployment of SMRs and MRs.

4.3. Future Role of AI, VR, AR, and IoT in Improving and Strengthening Safety of SMRs and MRs

Everyday there are new tools being brought into the market which use AI to perform different types of tasks. Looking at this emerging trend, participants were asked to provide their input on the potential role of AI, IoT, AR, VR, and UAVs in improving safety measures in the transportation and construction phase of SMRs and MRs. Participants had some interesting insights to share which could help relevant entities such as OSHA, researchers, and the construction industry to develop tools related to these technologies for better safety oversight and risk management during the construction and transportation phase of SMR and MR. The detailed inputs from the participants on the above technological tools are also discussed in the data analysis portion. In the future digital technology tools such as AI can enable predictive maintenance, risk assessment, and real-time monitoring, while IoT can provide sensor networks and remote monitoring capabilities. VR can offer realistic training and design visualization, while AR can provide on-site guidance and equipment maintenance support. Together, these technologies have the potential to revolutionize safety in SMRs and MRs by improving situational awareness, facilitating proactive measures, and enhancing decision-making processes, although their successful implementation will require careful planning and cybersecurity considerations.

5. Conclusion

This research has provided valuable insights into the safety considerations and challenges associated with the construction phase and transportation of SMRs and MRs. Through a comprehensive analysis of the literature and a questionnaire survey involving professionals in the nuclear industry, several key findings have emerged. It is evident that there are limitations in the existing safety guidelines provided by OSHA for SMRs and MRs transportation and construction. Specific guidelines addressing the safe transportation of these nuclear technologies are lacking, posing potential risks and uncertainties during their handling and movement. Moreover, the survey results have highlighted the importance of addressing worker safety in the nuclear construction domain. Factors such as heavy construction equipment handling, unguarded machinery, dust exposure, and transportation issues with SMRs and MRs have been identified as critical areas of concern. Specific factors have been identified that need to be addressed to develop new guidelines and strengthen existing ones. Strengthening guidelines and implementing effective safety measures in these areas are imperative to safeguard workers' well-being. Furthermore, the research has emphasized the need for a safety culture that promotes transparency, encourages a questioning attitude, and prioritizes worker safety. The integration of digital technology tools, such as AI, IoT, VR, and AR, holds promise for enhancing safety oversight and risk management during the construction and transportation phase of SMRs and MRs.

Overall, this research calls for the development of comprehensive and tailored guidelines that address the unique safety requirements of SMRs and MRs transportation and construction. The research limitations include the lack of holistic ccollaboration among stakeholders, including researchers, industry professionals, and regulatory bodies, which is essential to ensure the safe and successful implementation of these innovative nuclear technologies. By bridging the existing gaps in safety guidelines and promoting a strong safety culture, the nuclear industry can confidently embrace SMRs and MRs as sustainable and clean energy solutions while prioritizing the well-being of workers and protecting the environment. Further research and ongoing efforts are needed to continuously improve safety practices and mitigate potential risks associated with SMRs and MRs construction. Furthermore, it is imperative to adopt digital technology tools like AI, AR, VR, IoT, and UAVs proactively prior to the widespread implementation of SMRs and MRs in the future, aligning with the current demands of the era. If the matter is not solved before the practical deployment of these SMRs and MRs in huge numbers, it may not only impact economically but also have serious repercussions in the safety domain.

Author Contributions

Muhammad Kamran contributed to conceptualization, methodology, software, validation, analysis, investigation, data collection, draft preparation. Chengyi Zhang contributed to conceptualization, supervision, project administration, and funding acquisition. Danish Kumar contributed to data analysis, draft preparation. Sevilay Demirkesen and Huimin Li contributed to manuscript editing. All authors have read and agreed with the manuscript before its submission and publication.

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