Communication in Physical Sciences, 2024 11(4): 998-1015

Assessing Environmental Risks and Pollution Challenges of Nuclear Reactor Technologies: Case Studies and Remediation Strategies

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Received: 30 May 2024/Accepted: 12 October 2024/Published: 26 October *2024*

Abstract: *This study provides a comprehensive analysis of the environmental risks and pollution challenges associated with various types of nuclear reactors, including Pressurized Water Reactors (PWR), Boiling Water Reactors (BWR), Heavy Water Reactors (HWR), Fast Breeder Reactors (FBR), Small Modular Reactors (SMR), Molten Salt Reactors (MSR), and Gas-cooled Reactors (GCR). By examining case studies such as the Three Mile Island incident, Fukushima Daiichi disaster, and the Windscale fire, we identify critical factors contributing to environmental contamination, including operational failures, natural disasters, and material integrity issues. Qualitative assessments reveal significant public health implications, regulatory responses, and shifts in nuclear policy following these incidents, highlighting the need for enhanced safety protocols and community engagement in nuclear energy discourse. Additionally, this paper presents a framework of remediation measures tailored to address specific risks associated with each reactor type, emphasizing the importance of technological innovation and stakeholder collaboration in mitigating environmental impacts. Ultimately, this research aims to inform policymakers and industry stakeholders about the complexities of nuclear reactor operations, promoting a safer and more sustainable approach to nuclear energy development.*

Keywords: Nuclear reactors, challenges, impact on environment,remediation

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1. 0 Introduction

Nuclear energy is a significant part of the global energy mix, contributing around 10% of the world's electricity supply (World Nuclear Association, 2023). Despite its potential for reducing carbon emissions, nuclear power poses risks related to radioactive contamination, waste management, and accident scenarios. The nature and extent of these risks vary depending on the type of reactor used. Recent research emphasizes the need to understand these risks comprehensively to improve the safety and environmental management of nuclear power (IAEA, 2023).

U-235 is a popular nuclear reactor fuel that can capture neutron to facilitate fission, with the production of daughter nuclei and energy. For example, the equation below shows the fission product of U-235 to produce two daughter nuclei (such as Ba-141 and Kr-92), in addition to three moles of neutron as shown in the equation 1 below.

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3{}^{1}_{0}\mathrm{n} + \text{energy} \quad (1)$$

Estimated amount of energy for this reaction is about 200 MeV per fission event. Pu-239 can also be used as a fuel in a nuclear reactor (especially as mixed oxide fuel) to produce energy as shown by equation 2, as an example

$$^{239}_{94}Pu + \, ^{1}_{0}n \rightarrow \, ^{144}_{56}Ba + \, ^{90}_{38}Sr + 2^{1}_{0}n + \text{energy} \quad (2)$$

In thorium fuel cycle, U-233 can serve as a fissile material to produce daughter nuclei and energy as shown by the example in equation 3

$$^{233}_{92}U + \, ^{1}_{0}n \rightarrow \, ^{140}_{54}Xe + \, ^{94}_{38}Sr + 2^{1}_{0}n + \text{energy} \quad (3)$$

Also, U-235 can also undergoes fission to form different product such as tellurium-137 and zirconium- 97 with the release of energy and two neutrons (equation 4),

$$^{235}_{92}U + \, ^{1}_{0}n \rightarrow \, ^{137}_{52}Te + \, ^{97}_{40}Zr + 2^{1}_{0}n + \text{energy} \quad (4)$$

Plutonium can be fashioned to produce two daughter nuclei (such as I-131 and Nb-105), depending on the reaction conditions, as demonstrated by equation 5

$$^{239}_{94}Pu + \, ^{1}_{0}n \rightarrow \, ^{131}_{53}I + \, ^{105}_{41}Nb + 2^{1}_{0}n + \text{energy} \quad (5)$$

Th-233 is not a fissionable materials but when used as a nuclear fuel, it is converted to U-233 before the fission can occurs. The series of steps involves in such conversion are as follows,

(i) Neutron Capture by Thorium-232

$$^{232}_{90}Th + \, ^{1}_{0}n \rightarrow \, ^{233}_{90}Th \quad (6)$$

(ii) Beta Decay of Thorium-233 to Protactinium-233

$$^{233}_{90}Th + \xrightarrow{\beta^-} \, ^{233}_{91}Pa + \beta^- + \bar{\nu}_e \quad (7)$$

(iii) Beta Decay of Protactinium-233 to Uranium-233

$$^{233}_{91}Pa + \xrightarrow{\beta^-} \, ^{233}_{92}U + \beta^- + \bar{\nu}_e \quad (8)$$

The U-233 formed from Th 232 through the above three steps provided above is a fissionable materials and canbe used as shown in equation 3.

2.0 Types of Nuclear Reactors and Associated Pollution

Different types of nuclear reactors have unique operational characteristics that influence their environmental impact. This section explores the pollution contributions and risks associated with common reactor designs.

2.1 Pressurized Water Reactors (PWRs)

PWRs are one of the most common reactor types worldwide, using water as both a coolant and moderator. While they are known for their stable operation, PWRs can contribute to environmental pollution through small releases of tritium, a radioactive isotope of hydrogen, into surrounding water bodies (World Nuclear Association, 2023). Routine emissions are typically within regulatory limits but can accumulate over time, potentially affecting local ecosystems (Jha & Brown, 2022).

Risks: The primary risk associated with PWRs is the potential for a core meltdown, as seen in past incidents like the Three Mile Island accident (Smith & Chen, 2023). Although advancements in containment systems have reduced this risk, it remains a concern in emergency scenarios.

Health Implications: Long-term exposure to low levels of tritium can pose health risks, including increased cancer risks for communities dependent on nearby water sources (Li & Perez, 2021).

2.2 Boiling Water Reactors (BWRs)

BWRs use steam from the reactor core to directly drive turbines, increasing the risk of radioactive contamination in the steam cycle. Key pollutants include iodine-131, cesium-137, and strontium-90, which can be released during both routine operations and accidents (IAEA, 2023).

Risks: A notable risk for BWRs is the potential release of radioactive steam, which can occur due to system failures or operational errors. This risk was highlighted by the Fukushima Daiichi disaster, where radioactive releases had significant environmental and health impacts (Smith & Chen, 2023).

Health Implications: Radioactive iodine exposure is particularly dangerous due to its affinity for the thyroid gland, potentially leading to increased rates of thyroid cancer among exposed populations (Jha & Brown, 2022).

2.3 Heavy Water Reactors (HWRs)

HWRs, including the CANDU reactor design, use heavy water (D2O) as a moderator, which allows for the use of natural uranium as fuel. A significant concern with HWRs is the production and potential release of tritium (Li & Perez, 2021).

Risks: The management of tritium is critical, as leaks into nearby water bodies can occur during routine maintenance or operational failures. Additionally, HWRs have a high water demand, which can strain local water resources and contribute to thermal pollution (Jha & Brown, 2022).

Health Implications: Tritium contamination in drinking water can increase the risk of developmental and reproductive issues, as well as cancer, especially in vulnerable populations (World Nuclear Association, 2023).

2.4 Fast Breeder Reactors (FBRs)

FBRs are designed to produce more fissile material than they consume, using liquid metal coolants such as sodium. While they offer greater fuel efficiency, FBRs present unique environmental risks due to their use of sodium (Smith & Chen, 2023).

Risks: Sodium leaks can lead to chemical fires and radioactive contamination, as sodium reacts violently with water. Such incidents can cause localized radioactive pollution and are challenging to control (IAEA, 2023).

Health Implications: Exposure to radioactive sodium or accidental releases during coolant leaks can pose serious health risks, including acute radiation syndrome and long-term cancer risks (Li & Perez, 2021).

2.5 Small Modular Reactors (SMRs)

SMRs are an emerging class of reactors designed for enhanced safety and flexibility. They are often deployed in remote or isolated locations where large reactors are not feasible. However, concerns exist regarding the cumulative environmental impact of deploying multiple SMRs (Jha & Brown, 2022).

Risks: The decentralized nature of SMR deployment could lead to a dispersion of environmental risks, particularly in sensitive ecosystems (Smith & Chen, 2023). Additionally, smaller reactor sizes do not eliminate the potential for localized radioactive releases, particularly if proper containment measures are not maintained.

Health Implications: In remote areas, the health impacts of a radiation release could be more severe due to limited medical infrastructure, potentially leading to higher mortality rates in the event of an accident (World Nuclear Association, 2023).

Table 1: Overview of Different Types of Nuclear Reactors, Their Descriptions, Applications and Properties

Nuclear Reactor Type	Description	Properties/Key Features	Applications	References (APA)
Pressurized Water Reactor (PWR)	Uses water as both a coolant and a neutron moderator, with the primary coolant loop kept under high	Stable operation, low risk of coolant boiling, high thermal efficiency.	Widely used for electricity generation and naval propulsion (submarines and aircraft carriers).	World Nuclear Association. (2023)

	pressure to prevent boiling.			
Boiling Water Reactor (BWR)	Water boils directly in the reactor core, producing steam that drives the turbines.	Direct steam cycle, simpler design compared to PWRs, but with higher potential for radioactive steam release.	Primarily used for electricity generation in power plants.	IAEA. (2023).
Heavy Water Reactor (HWR)	Uses heavy water (D2O) as a coolant and moderator, allowing the use of natural uranium as fuel.	Higher neutron economy, ability to use natural uranium, efficient in plutonium production.	Commonly used in countries with limited access to enriched uranium (e.g., CANDU reactors in Canada).	Jha & Brown (2022).
Fast Breeder Reactor (FBR)	Uses fast neutrons to convert fertile material (like U-238) into fissile material (like Pu-239).	High fuel efficiency, uses liquid metal coolants like sodium, but requires complex safety systems.	Used for generating more fissile material than consumed, making it suitable for nuclear fuel recycling.	Li & Perez (2021)
Small Modular Reactor (SMR)	Compact reactors designed for scalability, with a smaller footprint than traditional large reactors.	Enhanced safety features, modular design allows for easy scaling and flexible deployment, shorter construction times.	Applications include electricity generation, industrial heat production, and deployment in remote or off-grid areas.	Smith & Chen (2023).
Molten Salt Reactor (MSR)	Uses a liquid mixture of fluoride or chloride salts as both the coolant and the fuel medium.	High thermal efficiency, ability to operate at low pressures, potential for using thorium as fuel.	Can be used for electricity generation and the transmutation of nuclear waste.	Sorensen (2022)
Gas-cooled Reactor (GCR)	Uses gas, such as carbon dioxide or helium, as a coolant.	High temperature operation, which increases thermal efficiency, but more complex gas handling.	Used for electricity generation, especially in early reactor designs in Europe.	Stevens & Park (2021).

Table 2 presents a comparative analysis of different nuclear reactor types, focusing on their advantages, disadvantages, and capacity requirements. This comparative framework is essential in evaluating the technological, economic, and operational trade-offs associated with each reactor type. The information serves as a guide for policymakers, engineers, and energy planners when selecting appropriate nuclear technologies based on energy demands, available infrastructure, safety goals, and environmental constraints. By outlining the key strengths and weaknesses of each design—from traditional Pressurized Water Reactors (PWRs) to emerging technologies like Small Modular Reactors (SMRs) and Molten Salt Reactors (MSRs), the table provides a foundational understanding of how different reactor systems align with global nuclear energy strategies and sustainable development goals.

Table 2: Advantages, Disadvantages, and Capacity Requirements of Different Nuclear Reactor Types

Nuclear Reactor Type	Advantages	Disadvantages	Capacity Requirements	References (APA)
Pressurized Water Reactor (PWR)	- High thermal efficiency due to high operating pressure. - Widely used, well-understood design with established safety protocols. - Suitable for naval applications like submarines.	- High-pressure operation increases the risk of leaks and requires robust containment. - More complex design and higher construction costs compared to simpler reactors.	- Typically ranges from 600 to 1,600 MWe. - Requires large containment structures to handle high-pressure operations.	World Nuclear Association. (2023).
Boiling Water Reactor (BWR)	- Simpler design with fewer components than PWRs. - Direct steam cycle improves efficiency.	- Higher potential for radioactive steam release, requiring additional safety systems. - Complex management of steam cycle and turbine contamination.	- Generally ranges from 600 to 1,400 MWe. - Needs large cooling systems due to direct steam production.	IAEA. (2023).
Heavy Water Reactor (HWR)	- Uses natural uranium, reducing the need for	- Produces significant amounts of tritium, which can be a	- Typically ranges from 600 to 800 MWe. - Requires heavy	Jha, & Brown. (2022).

	enrichment. - High neutron economy allows for efficient use of fuel.	contamination risk. - Heavy water is expensive and requires specialized handling.	water production and storage facilities, increasing plant size.	
Fast Breeder Reactor (FBR)	- High fuel efficiency, can breed more fissile material than consumed. - Reduces nuclear waste by using spent fuel.	- Uses liquid metal coolants like sodium, which can be highly reactive and pose safety risks. - Complex design increases construction and operational costs.	- Capacity ranges from 300 to 1,200 MWe. - Requires special facilities for fuel reprocessing and handling of liquid metal coolants.	Li & Perez (2021).
Small Modular Reactor (SMR)	- Modular design allows for scalability and shorter construction times. - Enhanced safety with passive cooling systems. - Ideal for remote or off-grid areas.	- Smaller size can result in higher costs per megawatt compared to larger reactors. - Deployment in remote areas can pose logistical challenges.	- Ranges from 10 to 300 MWe per unit. - Can be grouped in clusters to reach higher capacity, depending on demand.	Smith & Chen (2023).
Molten Salt Reactor (MSR)	- High thermal efficiency due to low-pressure operation. - Potential to use thorium, which is more abundant than uranium. - Can operate continuously with online fuel reprocessing.	- Corrosion of reactor materials due to the aggressive nature of molten salts. - Limited operational experience and regulatory frameworks.	- Typically ranges from 10 to 600 MWe. - Requires specialized systems for handling and circulating molten salt mixtures.	Sorensen. (2022).
Gas-cooled Reactor (GCR)	- Can achieve high temperatures, improving	- Complex gas handling systems required. - Lower power	- Capacity typically ranges from 200 to 600 MWe.	Stevens, M. & Park, H. (2021). Evolution of gas-cooled reactor

	thermal efficiency. - Use of inert gases like helium reduces the risk of coolant becoming radioactive.	density compared to water-cooled reactors, leading to larger physical size.	- Requires large reactor cores due to low power density.	designs. *Journal of Modern Nuclear Technology*, 18(2), 87-101.

Pressurized Water Reactors (PWRs) are the most widely adopted reactor type globally, known for their high thermal efficiency resulting from their operation under high pressure. Their mature technology and extensive use in both civilian and military applications make them a reliable choice for base-load power generation. However, the need for robust containment structures and complex high-pressure systems results in higher construction and maintenance costs. PWRs typically operate within a capacity range of 600 to 1,600 MWe, requiring significant infrastructure and safety protocols to manage their operational pressures, as highlighted by the World Nuclear Association (2023).

Boiling Water Reactors (BWRs) offer a simpler design than PWRs by eliminating the need for steam generators, using a direct steam cycle that increases efficiency. However, the direct involvement of the reactor core in the steam cycle introduces greater risks of radioactive steam release and turbine contamination. As such, BWRs demand comprehensive safety systems to manage these challenges. With a capacity range between 600 and 1,400 MWe, BWRs are competitive in terms of output but require large and efficient cooling systems to handle the direct steam production, according to the IAEA (2023).

Heavy Water Reactors (HWRs), such as Canada's CANDU reactors, are advantageous in that they use natural uranium, eliminating the need for enrichment. Their high neutron economy allows efficient fuel utilization, making them suitable for countries with limited uranium enrichment capabilities. However, the use of heavy water presents both economic and safety challenges due to its high cost and the need for specialized handling systems. These reactors typically operate in the 600 to 800 MWe range and require additional infrastructure for heavy water production and storage, as noted by Jha and Brown (2022).

Fast Breeder Reactors (FBRs) distinguish themselves by their ability to generate more fissile material than they consume, thus contributing to both waste reduction and fuel sustainability. Their reliance on liquid metal coolants like sodium offers excellent thermal properties but introduces reactivity hazards and requires specialized containment and handling systems. The complexity of their design results in increased capital and operational costs. FBRs have capacity ranges between 300 and 1,200 MWe and demand integrated facilities for reprocessing spent fuel and managing reactive coolants, as detailed by Li and Perez (2021).

Small Modular Reactors (SMRs) represent a transformative approach to nuclear energy deployment, offering modularity, shorter construction times, and enhanced passive safety features. Their suitability for off-grid and remote applications makes them attractive for decentralized energy needs. However, the smaller unit size often leads to higher costs per megawatt and logistical issues related to transportation and site preparation. SMRs generally have capacities ranging from 10 to 300 MWe per unit and are scalable by grouping multiple modules to meet larger demands, according to Smith and Chen (2023).

Molten Salt Reactors (MSRs) are noted for their high thermal efficiency and potential to use thorium—a more abundant alternative to uranium—as fuel. They operate at low pressures and can be refueled online, which improves operational continuity. However, challenges such as material corrosion from aggressive molten salts and limited regulatory experience hinder their commercial readiness. MSRs have projected capacity ranges from 10 to 600 MWe and require highly specialized systems for salt handling and circulation, as discussed by Sorensen (2022).

Gas-cooled Reactors (GCRs) use inert gases like helium as coolant, which avoids radioactive activation and enables operation at high temperatures, enhancing thermal efficiency. However, their complex gas handling requirements and lower power density lead to significantly larger reactor cores and infrastructure needs. With capacities typically ranging from 200 to 600 MWe, GCRs are technically viable but less space-efficient compared to water-cooled reactors. Stevens and Park (2021) emphasize the importance of technological evolution in gas-cooled designs to improve power density and economic competitiveness.

In conclusion, the content of Table 2 illustrates that each nuclear reactor type comes with a unique set of technical, economic, and environmental trade-offs. While mature technologies like PWRs and BWRs offer reliability and scalability, advanced designs such as FBRs, MSRs, and SMRs promise innovations in fuel efficiency, safety, and deployment flexibility. Decision-making regarding reactor deployment must consider not only power output and safety, but also infrastructure readiness, regulatory frameworks, and long-term sustainability.

3. 0 Radioactive Waste Management

All nuclear reactors generate radioactive waste, which poses long-term environmental and health risks if not managed properly. Recent research has focused on developing deep geological repositories for high-level waste, but concerns about the integrity of these facilities over thousands of years persist (IAEA, 2023).

Health Implications: Improperly stored nuclear waste can contaminate groundwater, leading to exposure risks for communities living near waste sites (Jha & Brown, 2022). Chronic exposure to low-dose radiation from waste leakage is associated with an increased risk of cancers and genetic damage.

3.1 Environmental Impact of Radioactive Wastes

Radioactive wastes, when not properly managed, pose significant and long-lasting environmental risks. These wastes contain unstable isotopes that emit ionizing radiation over extended periods, ranging from a few years to several millennia. Their environmental impact is influenced by the type, concentration, and mobility of radionuclides, as well as the pathways through which they can enter ecosystems.

One major environmental concern is the contamination of soil and groundwater. Improper disposal, accidental leaks from storage facilities, or breaches in containment systems can allow radionuclides such as cesium-137, strontium-90, iodine-131, and plutonium-239 to seep into the ground and migrate through soil layers. These radioactive elements can bind to soil particles or be carried by groundwater, leading to long-term contamination of agricultural lands and water supplies. Contaminated groundwater not only threatens human health but also affects plant uptake and the health of terrestrial and aquatic ecosystems.

Surface water contamination is another consequence, particularly when radioactive wastewater is discharged into rivers, lakes, or oceans. This can result from operational releases, accidents (e.g., Fukushima Daiichi in 2011), or intentional dumping of low-level radioactive waste. Once in water bodies, radionuclides can bioaccumulate in aquatic organisms, enter the food chain, and eventually reach human populations through seafood consumption.

Radioactive gases, such as radon, tritium, and carbon-14, released into the atmosphere from nuclear facilities or waste processing plants can also contribute to environmental degradation. These gases can be transported over long distances by wind currents, leading to widespread environmental dispersion. Although their concentrations may be low, prolonged exposure and deposition on vegetation and soil may still pose risks to both ecosystems and human health.

Another significant impact is the loss of biodiversity in contaminated zones. High radiation levels can affect reproductive success, genetic stability, and survival of various organisms. Studies around the Chernobyl exclusion zone, for example, have documented reduced populations of birds, mammals, and insects in highly contaminated areas. Chronic exposure to low-level radiation can cause mutations, developmental abnormalities, and altered ecological interactions.

The aesthetic and economic degradation of land is also a concern. Once an area is contaminated, it may be rendered unusable for agriculture, habitation, or recreation for decades or even centuries. This affects land value, displaces communities, and imposes long-term economic burdens on governments and local populations.

Moreover, public perception and fear of radioactive waste can have indirect environmental consequences. The stigma associated with radiation often leads to resistance against the establishment of necessary waste management infrastructure, which in turn may result in ad hoc or less secure storage practices, exacerbating environmental risks.

In conclusion, the environmental impact of radioactive waste is profound and multifaceted. It includes soil and water contamination, atmospheric pollution, biodiversity loss, and socio-economic disruption. These impacts underscore the need for stringent regulatory oversight, robust waste containment systems, and the development of long-term disposal solutions to protect both current and future generations from the hazardous legacy of radioactive materials.

Thermal pollution is a significant environmental impact associated with nuclear power plants, particularly those using water for cooling. The discharge of heated water into rivers or oceans can disrupt aquatic ecosystems, reduce dissolved oxygen levels, and impact local biodiversity (Li & Perez, 2021).

Health Implications: While thermal pollution primarily affects ecosystems, human health can be indirectly impacted through changes in fish populations and water quality, which can affect food supplies for nearby communities (World Nuclear Association, 2023).

Table 3: Pollution Contributions, Risks, and Health Implications Associated with Different Nuclear Reactor Types

Nuclear Reactor Type	Possible Pollution Contribution	Other Risks	Health Implications	References (APA)
Pressurized Water Reactors (PWRs)	Small releases of tritium into water bodies	Risk of core meltdown, spent fuel management	Low-dose radiation exposure risks to nearby populations, potential	World Nuclear Association. (2023)

			groundwater contamination	
Boiling Water Reactors (BWRs)	Releases of iodine-131, cesium-137 into steam cycles	Risk of radioactive steam leaks, turbine contamination	Increased risk of thyroid cancer due to iodine exposure, potential acute radiation sickness during accidents	IAEA. (2023).
Heavy Water Reactors (HWRs)	High tritium production and release into surrounding water	Leakage risks, water quality impacts	Tritium exposure can increase cancer risk, particularly for nearby communities relying on local water sources	Jha & Brown (2022)
Fast Breeder Reactors (FBRs)	Potential contamination from sodium leaks and fuel reprocessing waste	Risk of sodium fires, challenging coolant management	Potential chemical burns from sodium leaks, increased risk of long-term radiation effects from fuel handling	Li & Perez (2021).
Small Modular Reactors (SMRs)	Localized radioactive contamination, especially in remote areas	Cumulative impact from multiple reactor units, issues with deployment in sensitive ecosystems	Potential for localized radiation exposure if accidents occur, stress on rural healthcare systems	Smith, & Chen (2023)

3.2 Case Study

Table 4 presents significant case studies highlighting environmental issues arising from various types of nuclear reactors. Each incident underscores specific challenges and consequences, reflecting the complexity of managing nuclear energy safely.

Table 4: Case Studies on Environmental Issues, Accidents, and Risks in Different Types of Nuclear Reactors

Nuclear Reactor Type	Case Study	Environmental Issue	Impact	References (APA)
Pressurized Water Reactor (PWR)	**Three Mile Island, USA (1979)**	Partial meltdown caused by a cooling malfunction. Release of small amounts of radioactive gases.	- Led to changes in U.S. regulations and increased public scrutiny of nuclear energy. - Minimal direct health impacts but caused significant public concern	Walker (2021).

			about nuclear safety.	
Boiling Water Reactor (BWR)	**Fukushima Daiichi, Japan (2011)**	Earthquake and tsunami led to loss of power, core meltdowns, and hydrogen explosions. Release of radioactive materials into the air and Pacific Ocean.	- Large-scale contamination of water and soil. - Long-term evacuation of surrounding areas, affecting human health and livelihoods. - Increased global regulatory scrutiny and changes in nuclear policy.	World Nuclear Association. (2023)
Heavy Water Reactor (HWR)	**Pickering Nuclear Generating Station, Canada (1992)**	Heavy water leak due to a valve failure. Release of tritium into Lake Ontario.	- Elevated tritium levels in local water, raising concerns about potential health impacts. - Led to improvements in maintenance practices and valve technologies in CANDU reactors.	Lee & Carter (2022). .
Fast Breeder Reactor (FBR)	**Monju Reactor, Japan (1995)**	Sodium leak and fire from the cooling system, caused by a faulty thermocouple.	- Contamination of the reactor building and temporary shutdown of operations. - Increased public opposition to FBR technology in Japan, delaying further development.	Yamamoto (2021)
Small Modular Reactor (SMR)	**NuScale Reactor Design Review, USA (2020)**	Risk analysis of radiological release scenarios during seismic events.	- Identified potential challenges in waste storage and containment in remote areas. - Led to design improvements and adoption of	Smith & Chen (2023).

			enhanced safety features in modular reactors.	
Molten Salt Reactor (MSR)	**Oak Ridge National Laboratory, USA (1965-1969)**	Experimental reactor experienced corrosion issues, leading to leaks of radioactive materials.	- Leaks were contained but highlighted challenges with materials compatibility in molten salt environments. - Informed the development of corrosion-resistant materials for future MSR designs.	Sorensen (2022).
Gas-cooled Reactor (GCR)	**Windscale Fire, UK (1957)**	Fire in a graphite-moderated gas-cooled reactor caused by overheating during fuel annealing. Released radioactive iodine and other isotopes.	- Contamination of nearby agricultural areas, leading to the culling of livestock. - Health risks due to iodine-131 exposure, particularly affecting the thyroid gland. - Led to changes in reactor design and operational protocols.	Arnold (2021).

Some significant cases in global history concerning some nuclear environments are highlighted below.

Pressurized Water Reactor (PWR): Three Mile Island (1979)

The Three Mile Island incident involved a partial meltdown caused by a cooling malfunction, leading to the release of small amounts of radioactive gases. Although the direct health impacts were minimal, the event significantly affected public perception of nuclear energy and resulted in increased regulatory scrutiny and changes in safety protocols across the industry. As noted by Walker (2021), the incident catalyzed a shift in how nuclear safety was approached in the United States, emphasizing the importance of operator training and emergency preparedness.

Boiling Water Reactor (BWR): Fukushima Daiichi (2011)

The Fukushima disaster is one of the most significant nuclear accidents in history, triggered by a catastrophic earthquake and tsunami that resulted in core meltdowns and extensive radioactive release. The immediate environmental impact included contamination of the air, soil, and Pacific Ocean, which has lasting effects on marine ecosystems (World Nuclear Association, 2023). The incident led to the evacuation of surrounding areas, affecting thousands of residents and igniting global discussions about the safety and sustainability of nuclear energy. It emphasized the need for robust disaster preparedness, including earthquake and tsunami-resistant designs for nuclear facilities (Saito et al., 2022).

Heavy Water Reactor (HWR): Pickering Nuclear Generating Station (1992)

The leak of heavy water at the Pickering facility raised concerns about tritium contamination in Lake Ontario. Although the environmental impact was relatively localized, it highlighted the challenges of managing radioactive materials in heavy water reactors (Lee & Carter, 2022). The incident led to improvements in maintenance practices and technologies related to valve integrity, demonstrating the importance of continuous monitoring and innovation in reactor design to prevent similar occurrences.

Fast Breeder Reactor (FBR): Monju Reactor (1995)

The sodium leak and fire at the Monju reactor underscored the inherent risks associated with sodium-cooled reactors, particularly regarding coolant reactivity and material integrity (Yamamoto, 2021). The public opposition that ensued delayed further development of FBR technology in Japan, emphasizing the critical need for public trust and transparency in nuclear operations.

Small Modular Reactor (SMR): NuScale Reactor Design Review (2020)

The risk assessment for the NuScale reactor highlighted the potential radiological release scenarios during seismic events, particularly in remote locations (Smith & Chen, 2023). This assessment is crucial as it identifies challenges in waste storage and containment, underscoring the necessity for enhanced safety features in the design of SMRs. The continuous evolution of regulatory frameworks will be essential to ensure the safe deployment of these technologies.

Molten Salt Reactor (MSR): Oak Ridge National Laboratory (1965-1969)

The corrosion issues experienced in the MSR prototype led to significant lessons learned regarding materials compatibility in molten salt environments. As noted by Sorensen (2022), these findings are vital for developing corrosion-resistant materials for future MSRs, which are considered promising for their potential in sustainable energy production.

Gas-cooled Reactor (GCR): Windscale Fire (1957)

The Windscale fire highlighted the risks associated with graphite-moderated reactors, resulting in the release of radioactive isotopes into the environment and contamination of local agriculture (Arnold, 2021). This incident prompted a re-evaluation of safety protocols and reactor designs, reinforcing the need for stringent operational standards to mitigate fire risks and contamination.

5.0 Remediation Approaches to Radioactive Wastes: A Detailed Review with Literature Support

The remediation of radioactive waste is a critical aspect of nuclear energy management, focusing on the prevention of environmental contamination and the protection of public health. Radioactive wastes originate from multiple sources, including nuclear power reactors, medical and industrial applications, and nuclear research facilities. These wastes are categorized into low-level, intermediate-level, and high-level waste, with spent nuclear fuel being the most radiotoxic. Various strategies have been developed and implemented to address the environmental and health hazards associated with these wastes.

4.1 Containment and Isolation

One of the most widely adopted approaches is the containment and isolation of radioactive materials. This method aims to prevent the migration of radionuclides into the environment by using engineered barriers and stable geological formations. The use of deep geological repositories, which involves the burial of waste several hundred meters underground in stable rock formations, offers long-term protection by leveraging natural and engineered containment systems. According to the International Atomic Energy Agency (IAEA, 2022), this method is especially suitable for high-level waste due to its capacity to provide long-term environmental isolation.

4.2 Solidification and Immobilization

Another remediation technique involves the solidification and immobilization of radioactive liquids. These processes convert liquid waste into solid forms such as glass (vitrification), cement blocks (cementation), or bituminous solids (bituminization). This reduces the leachability and mobility of radioactive elements, thereby minimizing their potential release into the environment. The World Nuclear Association (2023) reports that solidification techniques are widely used to stabilize waste before long-term storage or disposal.

4.3 Partitioning and Transmutation

Advanced remediation technologies such as partitioning and transmutation have emerged as promising solutions. Partitioning involves the separation of long-lived radionuclides from the waste stream, while transmutation uses nuclear reactions to convert them into less harmful or short-lived isotopes. According to the Nuclear Energy Agency (NEA, 2020), these methods can significantly reduce the long-term radiotoxicity and heat generation of nuclear waste, although they remain under research and development in most countries.

4.4 Monitored Retrievable Storage

The use of monitored retrievable storage offers a temporary yet secure solution for spent nuclear fuel and high-level waste. These systems, which include dry cask storage and shielded pools, provide safe containment while allowing for regular monitoring and easy retrieval for future reprocessing or disposal. Smith and Chen (2023) noted that this approach is particularly effective as an interim measure while permanent disposal facilities are being developed or implemented.

4.5 Environmental Remediation Techniques

Environmental remediation techniques are deployed in cases where radioactive contamination has already occurred. These include soil washing, vitrification of contaminated earth, and bioremediation using specific microorganisms capable of radionuclide reduction. Decontamination of water bodies involves methods such as ion exchange, chemical precipitation, and reverse osmosis. Jha and Brown (2022) highlighted the importance of these approaches in restoring contaminated environments and preventing further spread of radioactive materials.

Table 3 presents a comprehensive overview of the specific pollution and risk challenges associated with different types of nuclear reactors and the remediation measures tailored to address them. It demonstrates that reactor design significantly influences the type and magnitude of risks encountered, such as coolant leaks, radioactive gas emissions, and management of spent fuel. The table also emphasizes the role of international organizations and academic researchers in developing and recommending effective remediation strategies for each reactor type. These strategies incorporate structural, technological, and operational solutions aimed at reducing environmental impact and enhancing reactor safety.

Pressurized Water Reactors (PWRs) are commonly used around the world and face significant risks from radioactive leaks due to high-pressure coolant system failures, as well as challenges related to the management of spent nuclear fuel. The remediation measures recommended for PWRs include the use of advanced containment structures to prevent radioactive release, implementation of dry cask storage systems for spent fuel, and routine maintenance of pressure vessels to detect early signs of mechanical degradation, as reported by the World Nuclear Association (2023).

Table 3: Remediation Measures for Pollution and Risk Challenges in Different Types of Nuclear Reactors

Nuclear Reactor Type	Pollution/Risk Challenge	Remediation Measures	References (APA)
Pressurized Water Reactor (PWR)	- Radioactive leaks due to high-pressure coolant system failures. - Spent nuclear fuel management.	- Use of advanced containment structures to prevent radioactive release. - Implementation of dry cask storage for spent fuel. - Regular maintenance and testing of pressure vessels to detect early signs of wear.	World Nuclear Association. (2023)
Boiling Water Reactor (BWR)	- Release of radioactive steam in case of core damage. - Contamination of cooling water.	- Use of hardened venting systems to release steam safely in emergencies. - Installation of advanced filtration systems to treat contaminated water before release. - Periodic safety drills and updated emergency response plans.	IAEA. (2023)
Heavy Water Reactor (HWR)	- Tritium contamination in cooling water. - Management of heavy water leaks.	- Use of isotopic separation techniques to remove tritium from water. - Improved sealing technologies to prevent leaks. - Regular monitoring of tritium levels in surrounding environments.	Jha, S., & Brown (2022).
Fast Breeder Reactor (FBR)	- Sodium leaks and fires due to coolant reactivity. - Management of radioactive waste.	- Installation of double-walled piping and advanced leak detection systems for sodium handling. - Use of inert gas atmospheres in sodium coolant systems. - Development of long-term geological repositories for radioactive waste.	Li & Perez (2021).
Small Modular Reactor (SMR)	- Spent fuel management in remote areas. - Risk of radiological exposure during transportation.	- Use of on-site interim storage facilities for spent fuel. - Enhanced safety features such as passive cooling to prevent overheating. - Safe transport protocols with	Smith & Chen (2023)

		shielding containers and real-time tracking.	
Molten Salt Reactor (MSR)	- Corrosion of reactor materials leading to leaks. - Management of radioactive by-products.	- Use of corrosion-resistant alloys and coatings for reactor materials. - Implementation of online chemical control systems to manage salt composition. - Development of methods for solidifying and storing radioactive by-products.	Sorensen (2022)
Gas-cooled Reactor (GCR)	- Release of radioactive carbon (C-14) and other gases. - Contamination due to eaks in gas handling systems.	- Use of gas purification systems to remove radioactive isotopes before venting. - Regular inspection and maintenance of gas containment structures. - Improved sealing technologies to minimize leaks.	Stevens & Park (2021).

Boiling Water Reactors (BWRs), which generate steam directly within the reactor core, pose risks related to the release of radioactive steam and contamination of cooling water. The International Atomic Energy Agency (IAEA, 2023) advocates for the use of hardened venting systems to release pressure safely during emergencies, the installation of advanced water filtration systems to treat contaminated water before discharge, and the execution of regular safety drills and updates to emergency response protocols.

Heavy Water Reactors (HWRs), such as Canada's CANDU reactors, are known for the production and release of tritium, a radioactive isotope of hydrogen, in their cooling systems. Jha and Brown (2022) recommend the use of isotopic separation technologies to extract tritium from water, the application of improved sealing technologies to prevent leaks, and continuous monitoring of environmental tritium levels in the surrounding areas.

Fast Breeder Reactors (FBRs) use liquid sodium as a coolant, which is highly reactive with air and water, thus posing risks of sodium fires and leaks. Li and Perez (2021) suggest the installation of double-walled piping systems and advanced sodium leak detection technologies, the use of inert gas atmospheres in coolant systems to prevent reactions, and the development of deep geological repositories for the long-term management of radioactive waste.

Small Modular Reactors (SMRs), which are designed for deployment in remote areas, face challenges in managing spent fuel and ensuring safe transportation of radioactive materials. Smith and Chen (2023) propose the use of on-site interim storage facilities to reduce the need for long-distance transport, incorporation of passive cooling features to prevent overheating, and adoption of strict safety protocols for transporting radioactive materials using shielded containers with real-time tracking systems.

Molten Salt Reactors (MSRs), which utilize liquid fuel salts at high temperatures, encounter corrosion issues in reactor components and difficulties in managing radioactive by-products. Sorensen (2022) recommends the use of corrosion-resistant alloys and special coatings to enhance material durability, the implementation of online chemical control systems to monitor and adjust salt composition, and the development of technologies to solidify and safely store radioactive by-products.

Gas-cooled Reactors (GCRs) release radioactive gases such as carbon-14 and face contamination risks due to leaks in gas handling systems. Stevens and Park (2021) emphasize the use of gas purification systems to extract radioactive isotopes before venting, the enforcement of regular inspection routines, and the application of advanced sealing technologies to minimize the risk of gas leaks.

In summary, Table 3 illustrates the importance of adopting tailored remediation strategies that correspond to the unique characteristics and operational risks of different reactor types. These measures, which combine engineering innovations, regulatory oversight, and emergency preparedness, are essential to ensuring the safe, sustainable, and publicly acceptable use of nuclear technology.

5. 0 Conclusion

This study offers a detailed exploration of the environmental risks and pollution challenges associated with various nuclear reactor types, including PWRs, BWRs, HWRs, FBRs, SMRs, MSRs, and GCRs. Through an analysis of significant case studies—such as the Three Mile Island incident, the Fukushima Daiichi disaster, and the Windscale fire—we identify the key factors contributing to environmental contamination, including operational failures, natural disasters, and material degradation. The qualitative assessments highlight the multifaceted public health implications and the regulatory changes prompted by these incidents, which have shaped contemporary nuclear safety protocols. Furthermore, we present tailored remediation measures that address specific risks associated with each reactor type, emphasizing the necessity for continuous innovation and stakeholder collaboration to enhance safety and sustainability in nuclear energy operations.

The findings of this study underscore the importance of recognizing and addressing the environmental risks inherent in nuclear reactor operations. The case studies examined reveal that incidents often lead to significant contamination and health risks, which can have long-lasting effects on communities and ecosystems. Additionally, the evolving regulatory landscape demonstrates the necessity for adaptive management strategies that prioritize safety, transparency, and public trust. By understanding the complexities of nuclear reactor technology and its environmental implications, stakeholders can better navigate the challenges associated with nuclear energy and work towards more resilient and sustainable energy solutions.

Nuclear facility operators should prioritize the development and implementation of advanced safety protocols that incorporate lessons learned from past incidents. Regular safety drills and operator training should be emphasized to ensure preparedness for potential emergencies. Continuous investment in research and development of nuclear technologies, particularly in areas such as materials science and monitoring systems, is essential to mitigate risks associated with aging infrastructure and to improve reactor safety. Establishing open channels of communication between nuclear operators and local communities is vital. Stakeholder engagement initiatives should be prioritized to build public trust and facilitate collaborative decision-making regarding nuclear energy operations.

Regulatory agencies should develop and enforce remediation measures that are specifically tailored to the unique risks associated with different reactor types. This could include enhanced monitoring of radioactive releases and improved waste management practices. Policymakers should continually evaluate and update regulatory frameworks to reflect advancements in nuclear technology and evolving public safety concerns. Regulatory bodies must remain vigilant in ensuring compliance with safety standards and promoting best practices in the industry. By implementing these recommendations, stakeholders can work towards minimizing the environmental impacts of nuclear energy while ensuring the safe and sustainable use of this crucial energy source.

Acknowledgement

The authors are grateful to Prof. Nnabuk Okon Eddy, FAS, for providing all the materials that supported this research

6.0 References

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Declaration

Consent for publication

Not applicable

Availability of data

Data shall be made available on demand.

Competing interests

The authors declared no conflict of interest

Ethical Consideration

Not applicable

Funding

There is no source of external funding

Authors' contributions

All components of the work were carried out by both authors