



Review Article

Radioactive Waste Management and Safety Frameworks for VVER-1200 Reactors at the Rooppur Nuclear Power Plant: A Comprehensive Review

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Abstract

Bangladesh's entry into the nuclear age with the construction of its first commercial nuclear power project, the Rooppur Nuclear Power Plant (RNPP), featuring two Generation III+ VVER-1200 units supplied by the Russian Federation, is a significant step towards achieving energy security. However, this significant technological advancement necessitates the parallel establishment of robust, internationally compliant strategies for the safe and sustainable management of radioactive waste (RW). This comprehensive review systematically synthesizes the proposed and implemented approaches for RW treatment, disposal, and regulatory oversight at the Rooppur Nuclear Power Plant, providing a critical analysis of the country's "National Policy on Radioactive Waste and Spent Nuclear Fuel Management-2019" and associated bilateral agreements. The primary finding highlights the strategic success of the policy, which mandates the repatriation of all high-level waste (Spent Nuclear Fuel, SNF) back to Russia, thereby eliminating the nation's most significant long-term nuclear liability. This agreement effectively offloads the burden of managing an estimated 50-60 tons of highly radioactive waste annually (fuel inventory and discharge estimates commensurate with 2.4 GWe plant capacity). Conversely, the review focuses on the domestic challenge of managing Low and Intermediate-Level Waste (LILW), examining the specialized technical systems for treating solid radioactive waste (SRW), liquid radioactive waste (LRW), and gaseous waste, including solidification processes and interim storage plans. Furthermore, the paper critically outlines the required strengthening of the regulatory framework under the Bangladesh Atomic Energy Regulatory Authority (BAERA) and identifies critical long-term gaps. These gaps include the absence of a formalized repository for final disposal of Low and Intermediate-Level Waste, the need for fully capitalized financial assurance funds, and the necessity for sustained investment in institutional capacity and human resources. This review contributes a vital synthesis to the literature

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on nuclear new build programs, particularly for developing nations, by detailing strategic solutions and outlining the immediate technical, regulatory, and financial priorities required to ensure the long-term safety and sustainability of the Rooppur Nuclear Power Plant.

Keywords

Radioactive Waste Management, Rooppur Nuclear Power Plant, Waste Treatment, Spent Nuclear Fuel, Bilateral Agreement, VVER-1200, Bangladesh Atomic Energy Regulatory Authority, International Atomic Energy Agency

1. Introduction

The Rooppur Nuclear Power Plant (RNPP), sometimes spelled Ruppur or Rooppur, is Bangladesh's first commercial nuclear power project. This project aligns with the global trend of developing nations seeking to diversify their energy mix and secure baseload capacity through low-carbon nuclear energy. While nuclear energy offers substantial environmental benefits over fossil fuels, its expansion intrinsically links every new program to the complex and highly regulated challenge of radioactive waste (RW) management. This challenge encompasses all waste streams from low-activity materials used in operations (Low-Level Waste, LLW) to the highly radioactive and heat-generating Spent Nuclear Fuel (SNF), which constitutes the High-Level Waste (HLW). The safe, long-term disposal of High-Level Waste (HLW) is universally acknowledged as the most significant hurdle in the nuclear fuel cycle, requiring either deep geological repositories or strategic international agreements. The construction of the Rooppur Nuclear Power Plant, which comprises two Generation III+ VVER-1200 reactors ($2 \times 1,200$ MWe), represents a landmark commitment to energy security [1]. Commissioning of these units and their full commercial operation has been a major national priority in recent years. As a new nuclear entrant, Bangladesh must ensure its radioactive waste management strategies are not only technically sound but also fully compliant with international safety standards and best practices established by the International Atomic Energy Agency (IAEA) [2].

While previous studies have addressed the general challenges and opportunities of nuclear power in Bangladesh and some have examined specific issues like radiological safety or public perception [3], there is a distinct lack of comprehensive literature that synthesizes the fragmented policy, regulatory and technical components into a single, cohesive framework for RNPP's waste management. Existing national planning documents and bilateral agreements are dispersed and often lack the integrated analysis required for a complete safety case [4]. Specifically, few published reviews consolidate the details of the National Policy on Radioactive Waste and Spent Nuclear Fuel Management-2019, the specifics of the Intergovernmental Agreement (IGA) for SNF repatriation and the status of domestic Low and Intermediate-Level Waste (LILW) treatment infrastructure into a critical evaluation [5].

This review addresses this critical gap by providing a comprehensive, single-source synthesis of the current status, policy decisions, technical equipment procurement and regulatory framework on RW management at the Rooppur Nuclear Power Plant. The significance of this article lies in three areas: primarily, it provides a clear model for the strategic solution (supplier-return fuel cycle) adopted by new nuclear nations to manage HLW; moreover, it outlines the specific technical and regulatory steps required for domestic LILW management; and in the end, it delivers a set of high-priority, point-based conclusions and recommendations necessary to guide policymakers and the regulatory body (BAERA) in ensuring the long-term safety, financial assurance and public acceptance of the program. This paper documents current arrangements, policy decisions, procurement of technical equipment, regulatory oversight, and outstanding needs for Rooppur Nuclear Power Plant (RNPP) waste management, using publicly available sources. The following sections cover the plant's technical specifications, waste categorization, treatment technologies, the regulatory landscape, on-site equipment and a final assessment of the residual challenges and gaps.

2. Radioactive Waste Management at the Rooppur Nuclear Power Plant (RNPP)

2.1. Site Characteristics and Geomorphology

The Rooppur Nuclear Power Plant (RNPP) area in Iswardhi and Lokkhikunda, Pabna district, Bangladesh was located between $24^{\circ}03'$ and $24^{\circ}15'$ north latitudes and between $89^{\circ}00'$ and $89^{\circ}11'$ east longitudes, the westernmost upazila of Pabna District in Rajshahi Division. 120 km (75 miles) north of the capital, Dhaka. The area has a tropical monsoon climate with seasonality in rainfall distribution; the mean annual rainfall and temperature are 1872 mm and 36.8°C , respectively. The upazila occupies an area of 250.89 sq. km [6]. It is bounded by Lalpur and Baraigram Upazila to the north, Kushtia Sadar and the Padma River to the south, Pabna Sadar and Atgharia Upazila to the east, Bheramara and Lalpur Upazila and the Padma River to the west.

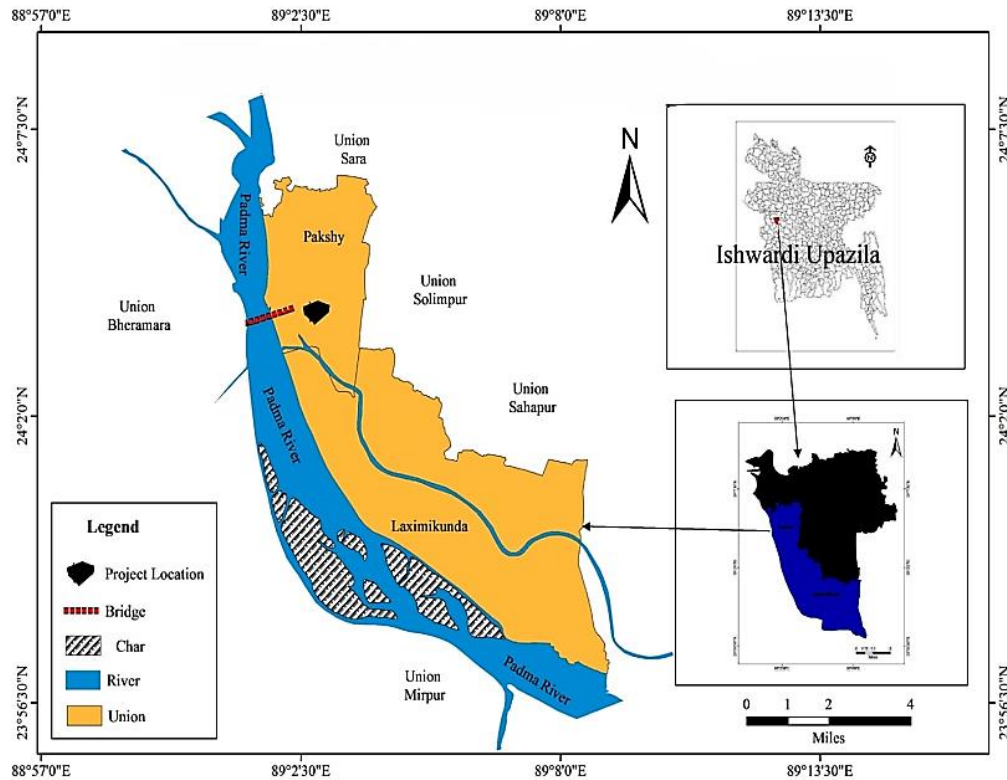


Figure 1. Location of the Rooppur Nuclear Power Plant area, Ishwardi, Pabna, Bangladesh [7].

2.2. Nuclear Technologies: The VVER-1200

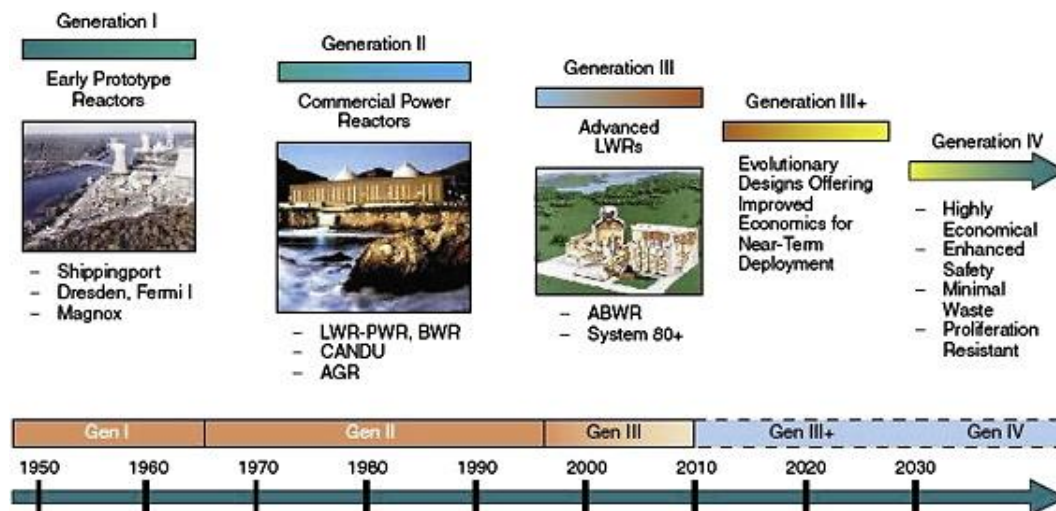


Figure 2. Generations of Nuclear Technologies [8].

Nuclear power technologies have evolved through several distinct generations, classified as Generation I, II, III, III⁺ and IV. Generation I reactors were early prototypes developed during the 1950s and 1960s, most of which have now been decommissioned. Generation II refers to commercial power reactors built mainly between the 1970s and 1990s, including

widely deployed designs such as Pressurized Water Reactor (PWR), Boiling Water Reactor (BWR), CANDU (Canada Deuterium Uranium), Advanced Gas-cooled Reactor (AGR) and VVER (Vodo-Vodyanoi Energetichesky Reactor) which is a Russian-designed PWR, typically operating for about 40 years [9]. Generation III reactors represent advanced versions

of these light-water systems, featuring improvements in fuel technology, thermal efficiency, modular construction, and safety systems, extending operational lifetimes to around 60 years. Generation III⁺ designs further enhance safety and reliability through evolutionary innovations and are the current

standard for new nuclear builds worldwide. Looking ahead, Generation IV reactors, expected to emerge commercially around 2030, aim to achieve higher sustainability, efficiency, and inherent safety, marking the next frontier in nuclear energy development [10].

2.3. Rooppur Nuclear Power Plant Layout and VVER-1200 Specifications



Figure 3. Schematic layout of a typical VVER plant at Rooppur Nuclear Power Plant [11].

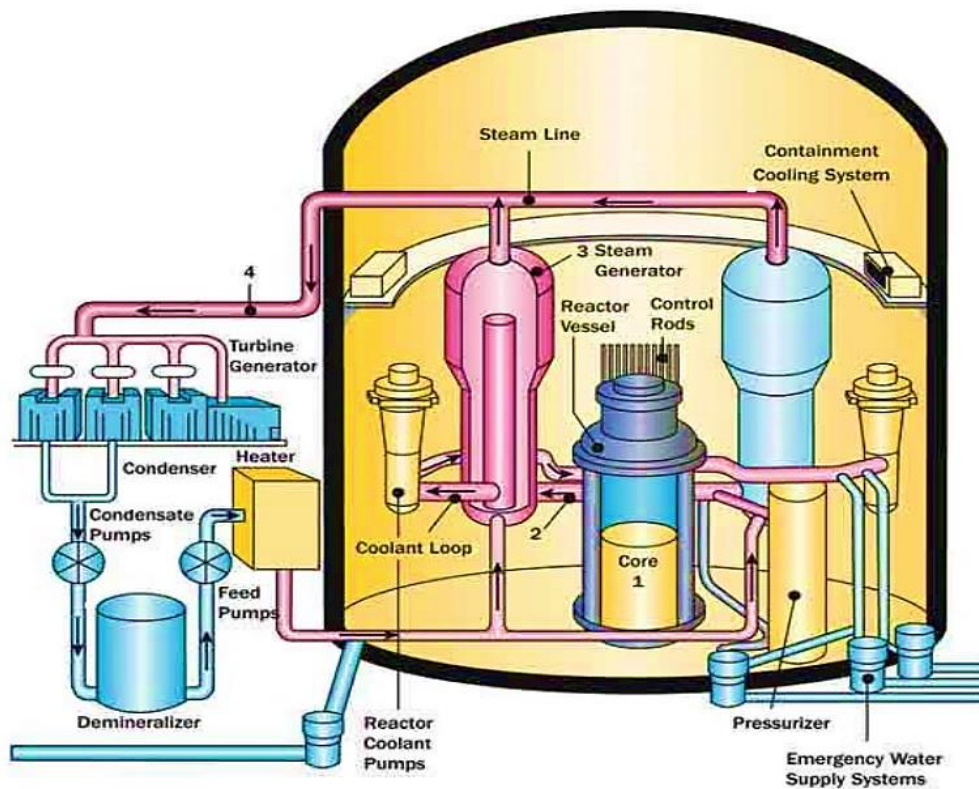


Figure 4. Schematic diagram of reactor head VVER-1200 Gen-III⁺ at Rooppur Nuclear Power Plant [12].

At the Rooppur Nuclear Power Plant, advanced Russian technology is being implemented, with Rosatom serving as the main reactor supplier. The plant features the VVER-1200/V-523 model, whose reactor installation at RNPP Unit-1 began in 2018 [13]. The VVER, formerly known as Water-Water Energetic Reactor (WWER), is a pressurized water reactor design developed in Russia, known for its high output

and robust safety systems. Since the 1960s, Rosatom has constructed and supplied 67 VVER units worldwide. The V-523 model selected for Bangladesh represents the most powerful version of this series, capable of generating approximately 1,158 MWe per unit [14]. Figures 3 and 4 illustrate the typical layout of a VVER nuclear plant and the schematic design of the VVER-1200 reactor head, respectively.

Table 1. Basic specification of RNPP and Key specifications of VVER-1200 Gen-III⁺ [15].

Parameters: Value/ Type	Parameters: Value/ Type
Project Owner: Bangladesh Atomic Energy Commission (BAEC)	Design Service Life: 60 years (min.) to 90 years (max.)
Technology Supplier: Rosatom (Russian Federation)	Gross Electrical output: 1,200 MWe (per unit)
Reactor Type: VVER-1200 / V-523 (Generation III ⁺)	Thermal output: 3,200 MWt (per unit)
Number of Reactors: 2 Units	Heat supply capacity: 300 MWt
Power Units 2: RNPP-I and RNPP-II	Plant Efficiency: >90%
Cooling Source: Padma River	Labor-Power Ratio: 0.35 to 0.5 person/MW
Cooling Infrastructure: 2 Natural Draft Cooling Towers	Fuel Campaigning Duration: 4 years (min.)
Net Electrical Output: approx. 1,158 MWe (per unit)	Max Fuel Burn-up: 60 MWd/kgU
Total Plant Capacity: 2,400 MWe (gross)	Refuelling Frequency: 12 to 18 months

2.4. Radioactive Waste Categorization

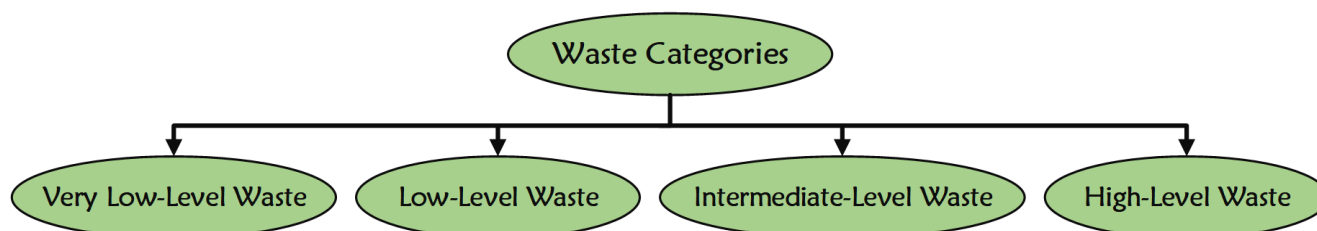


Figure 5. Radioactive waste categories of nuclear power plants.

Nuclear power plants generate several types of radioactive waste. Very low-level waste (VLLW) includes slightly contaminated materials such as clothing, filters and construction waste. Low-level waste (LLW) consists of items such as contaminated tools, resins and sludges with low activity [16]. Intermediate-level waste (ILW) contains higher activity items, for example, reactor internals and some ion-exchange resins, which require shielding but not heat management. High-level waste (HLW), also referred to as spent nuclear fuel (SNF), consists of used fuel assemblies that are highly radioactive and generate significant heat, requiring cooling and shielding [17]. These categories are standard and are used in planning for Rooppur Nuclear Power Plant (RNPP). Waste volumes depend on operational practices, fuel cycle choices and decommissioning strategies.

2.5. Hazards of Radioactive Waste

The main risk of radioactive waste arises from its radioactive emissions, which can cause both somatic and genetic damage to humans. Acute exposure to high radiation doses may result in immediate injuries, while long-term low-level exposure can lead to chronic effects such as leukemia, cancers, cataracts and developmental disorders. Environmentally, radioactive decay generates heat in deep geological repositories, altering subsurface temperature, fluid flow, and chemical conditions, which can affect rock stability and contaminant migration. Moreover, radionuclides may leach from waste containers into groundwater, eventually reaching the biosphere and posing long-term ecological and health hazards [18].

2.6. Radioactive Waste Treatment Stages

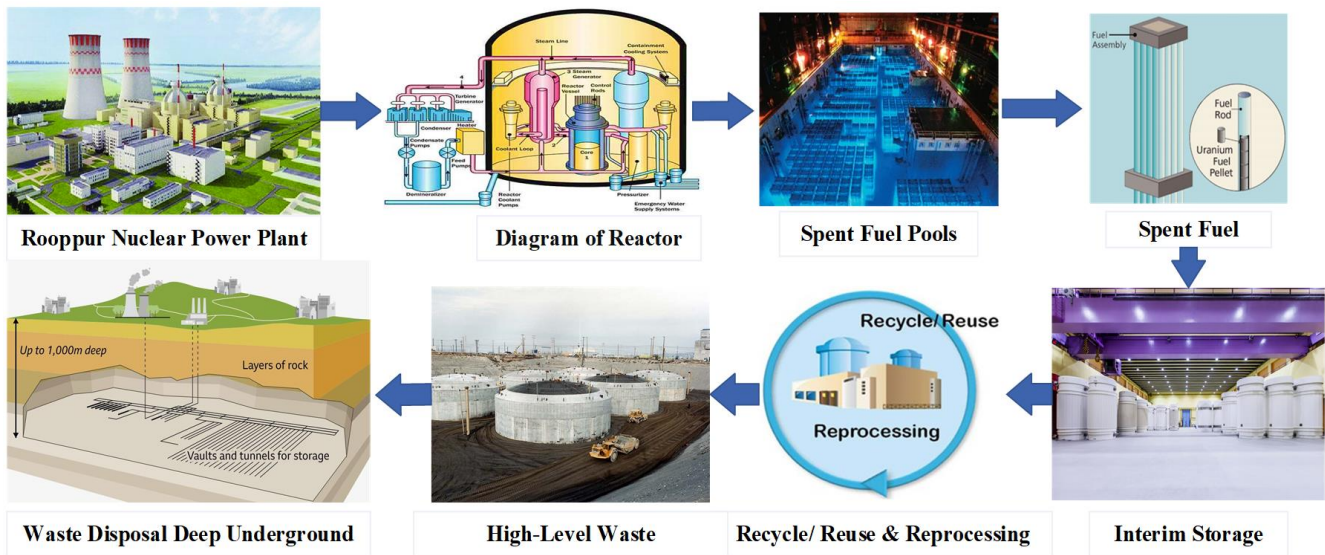


Figure 6. Radioactive Waste Treatment stages at Rooppur Nuclear Power Plant (modified from Kim et al. 2011) [19].

Various radioactive waste disposal methods such as deep-seabed disposal, polar ice sheet disposal, and space disposal have been explored. However, deep geological disposal is regarded as the most technically feasible, safe, cost-effective and environmentally responsible solution for managing high-level and long-lived radioactive wastes. Radioactive waste varies in type and activity, requiring specific treatment methods based on its physical form and radioactivity level. Generally, waste management includes the treatment of gaseous, liquid, and solid wastes. Radioactive gases are processed through filtration and adsorption systems to remove radionuclides before being safely released into the atmosphere within regulatory limits. Liquid radioactive waste, being highly mobile and corrosive, is treated using methods such as chemical precipitation, ion exchange, and electrodialysis to remove contaminants [20]. The resulting residues are then solidified to immobilize radionuclides and ensure long-term stability. Effective solidification must provide mechanical strength, resistance to leaching, and ease of transport and storage to maintain safety throughout the waste's lifecycle.

2.7. Estimated Magnitudes

Publicly available RNPP planning documents and national studies indicate that a typical commercial PWR/ VVER operation will generate measurable quantities of VLLW/ LLW/ ILW annually [21]. That spent fuel accumulates each fuel cycle and requires either long-term on-site storage or re-routing to fuel suppliers. Specifically, based on IAEA estimates of 27 tons of HLW per 1000 MWe annually, the RNPP's total capacity of 2.4 GWe (2,400 MWe) is expected to produce approximately 50 to 60 tons of high-level waste every year [22].

Exact volumes for RNPP are part of the plant's safety documentation and national planning; independent studies for RNPP propose interim storage for VLLW and strategies for spent fuel repatriation [23].

3. Regulatory and Safety Policy Frame-work for VVER-1200 Reactors

3.1. National Policy and Regulatory Bodies

Bangladesh has established a national policy on radioactive waste and spent fuel management, approved by the Cabinet in 2019, which outlines responsibilities for producers, interim storage and plans for long-term solutions [24]. The Bangladesh Atomic Energy Regulatory Authority (BAERA) is the national agency responsible for licensing, inspection and enforcing radiation and waste safety standards. The BAEC is a key implementing body and the owner/stakeholder of RNPP through Nuclear Power Plant Company Bangladesh Limited. The IAEA has carried out review missions, such as IRRS, to offer recommendations for strengthening regulatory oversight [25].

3.2. Key Policy Elements Relevant to RNPP

The 2019 policy requires waste producers to manage and store waste at their sites and to be capable of handling waste until government or designated facilities take over. Bangladesh and Russia signed an intergovernmental agreement (IGA) specifying that spent fuel from Rooppur Nuclear Power Plant

will be repatriated to Russia for temporary storage, reprocessing or other management, establishing a supplier-return fuel cycle [26]. This is critical because it reduces the need for Bangladesh to host long-term spent fuel repositories.

4. On-site Waste Treatment and Technical Equipment for RNPP

4.1. Liquid Radioactive Waste Management Equipment

Contracts have been signed for the supply of equipment and systems to treat liquid radioactive wastes at Rooppur Nuclear Power Plant (RNPP). In mid-2022, Atomstroyexport (the general contractor) contracted Sverdniikhimmash (part of AtomEnergomash) to design, manufacture and deliver liquid radioactive waste (LRW) treatment equipment, with delivery and pre-commissioning support planned between 2022 to 2023 [27]. These systems typically include pre-filtration, chemical treatment, ion exchange, evaporation, and sludge handling modules, as well as conditioned waste packaging.

4.2. Solid and VLLW Handling Interim Storage

Studies and conference contributions indicate plans for an interim surface storage facility for very low-level waste (VLLW) at Rooppur Nuclear Power Plant (RNPP) to hold conditioned waste packages for monitoring and eventual disposal or release in accordance with regulatory limits. Interim storage design focuses on robust packaging, restricted access, environmental monitoring, and record-keeping [28].

4.3. Spent Fuel Handling and Repatriation Logistics

Under the IGA, spent fuel will be repatriated to Russia. Practically, this requires on-site systems for spent fuel pool cooling, drying and cask loading facilities, transport packaging consistent with international transport regulations, and secure logistics coordination for shipments to the supplier country [29]. Rooppur Nuclear Power Plant (RNPP) design incorporates spent fuel pools and initial on-site storage capacity consistent with VVER-1200 designs, while long-term management leverages repatriation.

4.4. International Engagement and Safety Reviews

The International Atomic Energy Agency (IAEA) missions and international cooperation form part of the Rooppur Nuclear Power Plant (RNPP) safety and waste management oversight. The IAEA's Integrated Regulatory Review Service and other technical support missions help Bangladesh strengthen regulatory frameworks, emergency preparedness, transport

safety, and waste management practices [30]. Cooperation with Russian technical partners (Rosatom, AtomEnergomash) include technology transfer, supply of waste treatment equipment and implementation support.

5. Challenges and Identified Gaps

5.1. Institutional Capacity and Human Resources

Operating an NPP and a comprehensive waste management program requires experienced regulatory staff, trained operators, waste safety specialists and long-term institutional capacity for monitoring and record retention. Bangladesh is building capacity but will require continued training, recruitment and retention strategies. This is emphasized in recent literature and national SWOT analyses [31].

5.2. Public Perception and Stakeholder Engagement

Surveys indicate public concerns over radioactive waste and environmental risk. Transparent communication, community engagement and clear demonstration of safety measures are essential to maintain social license and minimize misinformation [32]. Studies in Bangladesh reveal ongoing concerns that must be addressed through targeted outreach [33].

5.3. Long-term Disposal Strategy and Financial Planning

While the Intergovernmental Agreement (IGA) for repatriation reduces near-term spent fuel burdens, long-term strategies for low-level and intermediate-level waste disposal, decommissioning liabilities and funding mechanisms (waste funds, operator responsibility) must be formalized and financed over decades [34]. Interim storage designs must be robust to bridge the gap to a final disposal solution [35].

5.4. Transport and Cross-border Logistics for Repatriation

Repatriation requires safe transport by road [36], rail or sea, international regulatory compliance (International Atomic Energy Agency Type B packages for SNF), bilateral coordination and contingency planning [37]. Ensuring secure, timely repatriation over the plant's lifetime is logistically non-trivial.

6. Summary

It has been shown in Table 2 that the radioactive waste streams at the Rooppur Nuclear Power Plant (RNPP) are comprehensively categorized according to international standards

VLLW, LLW, ILW and HLW. The table summarizes the origin, physical form, and initial treatment requirements for fifteen distinct waste types derived from the VVER-1200 operations. Crucially, the data distinguishes between high-activity, heat-generating Spent Nuclear Fuel (SNF), which is slated

for repatriation 50 to 60 tons annually and the lower-activity wastes (Very Low-Level Waste, Low-Level Waste and Intermediate-Level Waste), which are managed domestically through methods like filtration, ion exchange and subsequent solidification and interim storage.

Table 2. Observation of recent investigations on various types of radioactive waste treatment and management at RNPP.

SL No.	Waste Category	Specific Waste Type/ Form	Treatment/ Composition (Source)	Ref.
01.	Very Low-Level Waste	Clothing	Slightly contaminated materials.	[16]
02.	Very Low-Level Waste	Filters	Slightly contaminated materials, from gas/ liquid processing	[16]
03.	Very Low-Level Waste	Construction Waste	Slightly contaminated materials (e.g., during de-commissioning)	[16]
04.	Low-Level Waste	Contaminated Tools	Low activity items	[16]
05.	Low-Level Waste	Resins (non-specific, implied)	Low activity items, generated from ion-exchange processes	[16]
06.	Low-Level Waste	Sludges	Low activity items, often resulting from liquid waste treatment	[16]
07.	Intermediate-Level Waste	Reactor Internals	Higher activity items, require shielding but not heat management	[17]
08.	Intermediate-Level Waste	Some Ion-Exchange Resins	Higher activity items, require shielding but not heat management	[17]
09.	Liquid Radioactive Waste	Corrosive Liquids	Highly mobile and corrosive; treated by chemical precipitation, ion exchange, and electrodialysis	[20]
10.	Liquid Radioactive Waste	Aqueous Effluents	Liquid streams requiring removal of contaminants	[20]
11.	High-Level Waste	Spent Nuclear Fuel	Highly radioactive, generates significant heat, consists of used fuel assemblies	[22]
12.	High-Level Waste Quantity	50-60 tons annually	Estimated annual production based on RNPP's 2.4 GWe capacity	[22]
13.	Gaseous Waste	Radioactive Gases	Processed through filtration and adsorption systems to remove radionuclides	[23]
14.	Solid Waste (General)	Conditioned Waste Packages	Residues from liquid treatment or processed VLLW/ LLW/ ILW	[23]
15.	Solid Waste (General)	Sludge Handling Modules	Residues generated from liquid waste treatment (mentioned in LRW equipment)	[27]

7. Conclusions

Rooppur is a landmark project that demands best-in-class radioactive waste management. The key strength is the strategic policy choice outlined in the 2019 National Policy and the Intergovernmental Agreement (IGA) for Spent Nuclear Fuel (SNF) repatriation, which eliminates the most significant long-term high-level waste (HLW) disposal burden for Bang-

ladesh. Furthermore, the procurement of modern LRW treatment systems is a necessary step towards safe operations. However, the domestic challenge for LILW disposal, long-term financing and institutional capacity-building (especially for BAERA) remains paramount. The continuous implementation of IAEA recommendations, securing the financial fund and building enduring public trust through transparency are the critical priorities that will define the long-term sustainability and safety of Bangladesh's nuclear energy program. Based on this evaluation, the following recommendations are critical

for ensuring the long-term safety and sustainability of waste management at the Rooppur Nuclear Power Plant:

- 1).Continue to implement International Atomic Energy Agency, Integrated Regulatory Review Service recommendations and invest in regulatory training, inspection resources and enforcement mechanisms.
- 2).Establish and capitalize a waste management fund (operator contributions) that covers interim storage, conditioning, transport and eventual disposal/decommissioning costs.
- 3).Ensure vendor deliveries e.g., Sverdniikhimmash equipment, are fully tested and independent verification of performance is performed before routine operation.
- 4).Regularly review and exercise repatriation logistics, ensure cask loading and transport infrastructure meet International Atomic Energy Agency standards and maintain legal/contractual clarity with supplier countries.
- 5).Interim facilities for very low-level waste/ low-level waste should include environmental monitoring, maintenance plans and robust recordkeeping to allow future re-evaluation.
- 6).Implement ongoing public information campaigns, transparent monitoring results and community liaison offices to build trust.
- 7).Expand specialized training programs with the International Atomic Energy Agency and international partners in waste conditioning, decommissioning planning and transport safety.

Abbreviations

BAERA	Bangladesh Atomic Energy Regulatory Authority
BAEC	Bangladesh Atomic Energy Commission
ESIA	Environmental and Social Impact Assessment
IAEA	International Atomic Energy Agency
IRRS	Integrated Regulatory Review Service
IGA	Intergovernmental Agreement
NPCBL	Nuclear Power Plant Company Bangladesh Limited
RNPP	Rooppur Nuclear Power Plant
m ³	Cubic Meter (Unit of Volume)
GWe	Gigawatts Electric (Electrical Output)
MWe	Megawatt Electric (Electrical Output)
MWt	Megawatts Thermal (Thermal Output)
VVER-1200	Vodo-Vodyanoi Energetichesky Reaktor (Water-Water Energetic Reactor-1200 MWe)

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Conflicts of Interest

The authors declare no conflicts of interest.

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