

“Challenges of Radioactive Waste Management and Spent Nuclear Fuel Handling in the Context of Nuclear Energy Development”

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Introduction

In recent decades, nuclear energy has become an integral part of the global energy system, providing a significant share of electricity for both developing and developed countries. With the growing energy demands driven by rapid industrial development, technological advancements, and population growth, nuclear power plants represent one of the most efficient and low-carbon energy sources. However, along with the advantages of nuclear energy a serious challenge arises—the management of radioactive waste (RW) and spent nuclear fuel (SNF).

To meet the increasing energy demands required for the growth of industries, artificial intelligence, cryptocurrency, and electric transport, the construction of new nuclear power plants and the modernization of existing ones are necessary. At the same time, it is essential to recognize that the volume of spent radioactive materials (waste) will only continue to grow.

Nuclear energy is an ideal option for sustainable power generation due to its long lifespan and ability to produce electricity with minimal greenhouse gas emissions. However, this form of energy generation produces radioactive waste, which must either be safely stored and disposed of or reprocessed. Long-term sustainable solutions for radioactive waste management require a combination of technical expertise, regulatory oversight, and continuous research to ensure safe containment and final disposal.

The generation of radioactive waste is an inevitable byproduct of nuclear energy, making its safe storage and disposal crucial for environmental protection and human health. As energy production and, consequently, waste volumes increase, the need for reliable and efficient waste management systems becomes more pressing. Improper handling of radioactive waste can lead to serious environmental disasters and health threats, emphasizing the significance of this issue in modern society.

Modern approaches to radioactive waste management require a comprehensive strategy that includes both scientific research and technological development. Currently, there are multiple classifications of radioactive waste, complicating their disposal and requiring specialized treatment and storage methods. Many countries have already developed and implemented effective systems for safe waste management. However, in Russia, this issue demands special attention due to the accumulated volumes of radioactive materials and the need for new infrastructure facilities.

Additionally, public perception of nuclear energy and its waste is often based on fear and distrust, highlighting the importance of transparency in waste management and public awareness efforts regarding safety measures. In an era of globalization and increasing international cooperation, sharing experiences and jointly addressing radioactive waste disposal challenges are crucial for the sustainable development of nuclear energy.

This article examines the pressing issues of radioactive waste and spent nuclear fuel management, analyzing existing approaches, challenges, and prospects, and emphasizing the significance of scientific research and technological innovations in solving these problems. Given the increasing reliance on nuclear energy, it is vital to ensure safe waste management, which will ultimately contribute to sustainable development both at the national and global levels.

Radioactive Waste Classification and Disposal Methods

Radioactive waste refers to materials and substances that can no longer be used, as well as equipment and products (including spent ionizing radiation sources) that contain radionuclides exceeding levels established by the Russian government.(1)

There are various classifications of radioactive waste. According to the classification of the Russian State Corporation “Rosatom,” there are six classes of radioactive waste based on their radionuclide composition. (2)

Table 1. Classification of Radioactive Waste

Class of RW	Type of RW	Composition of RW	Disposal Methods
1	SRW (Solid Radioactive Waste)	<ul style="list-style-type: none"> - Materials - Equipment - Products - Solidified LRW (Liquid Radioactive Waste) - High-heat-generating HLW (High-Level Waste) 	Final isolation in deep geological repositories with preliminary storage
2	SRW	<ul style="list-style-type: none"> - Materials - Equipment - Products - Soil -Solidified LRW - Sealed sources of ionizing radiation (Categories 1 & 2) - Low-heat-generating HLW - Long-lived ILW (Intermediate-Level Waste) 	Final isolation in deep geological repositories
3	SRW	<ul style="list-style-type: none"> - Materials - Equipment - Products - Soil - Solidified LRW - Sealed sources of ionizing radiation (Category 3) 	Final isolation in near-surface disposal facilities at depths up to 100 meters

		<ul style="list-style-type: none"> - Short-lived ILW - Long-lived LLW (Low-Level Waste) 	
4	SRW	<ul style="list-style-type: none"> - Materials - Equipment - Products - Soil - Solidified LRW - Biological objects - Sealed sources of ionizing radiation (Categories 4 & 5) - Short-lived LLW - Long-lived VLLW (Very Low-Level Waste) 	Final isolation in near-surface disposal facilities at ground level
5	LRW	<ul style="list-style-type: none"> - Organic and inorganic liquids, slurries, sludges - Short-lived ILW - Long-lived LLW 	Final isolation in existing deep geological repositories
6	-	Radioactive waste generated during uranium ore mining and processing, as well as mineral and organic raw materials with elevated natural radionuclide content	Final isolation in near-surface disposal facilities

Many people often confuse radioactive waste (RW) with spent nuclear fuel (SNF), which can still be reused if reprocessed. SNF contains significant amounts of uranium-235 and uranium-238, plutonium, and other isotopes valuable for medicine and science. Although reprocessing is a complex technology, many countries possess this capability. Thus, SNF is considered a valuable secondary resource. In the past, SNF was deemed useless and highly hazardous waste. However, the disposal or burial of radioactive waste remains a pressing issue due to the expansion and development of nuclear energy.

The most hazardous radioactive waste (RAW) is classified as Class 1-2 waste, which includes materials and equipment from nuclear facilities that have reached the end of their service life, solidified liquid radioactive waste (LRW), and similar materials. These must be permanently disposed of at great depths, as the half-life of the isotopes they contain can reach hundreds of thousands of years. Class 3-4 waste consists of low- and intermediate-level short-lived radioactive waste (which will become non-hazardous in approximately 300 years), such as protective clothing and radionuclide-contaminated debris. These can be disposed of in near-surface disposal facilities (NSDF) at depths of up to 100 meters. Class 5 waste includes liquid waste generated during the operation of nuclear facilities, such as water used for cleaning floors at nuclear power plants. Class 6 waste consists of radioactive waste produced during the extraction of uranium and other minerals with naturally elevated radiation levels, making them relatively the least hazardous. (3)

Global and Russian Approaches to Radioactive Waste Management

Worldwide, companies operating nuclear power plants face daily challenges in disposing of spent fuel and radioactive waste. In the United States alone, there are more than 90,000 metric tons of high-level radioactive waste stored near nuclear power plants and weapons production facilities, emitting radiation that poses a serious risk to human health and the environment. Most high-level radioactive waste is awaiting permanent disposal in deep geological repositories; however, not a single such repository is currently operational in the U.S. This is confirmed by publications from the National Nuclear Security Administration (NNSA) and reports from the U.S. Department of Energy (DOE). (4)

In the Russian Federation, approximately 500 million cubic meters of radioactive waste (RAW) have been accumulated since the commissioning of the first nuclear power plant.

The majority of this volume is located in the Chelyabinsk region, in the bottom sediments of the Techa Cascade Reservoirs, as well as in the Ulyanovsk region, the Udmurt Republic, and the Krasnoyarsk and Zabaykalsky territories. These are restricted-access areas where a barrier system has been established to prevent radiation from escaping into the environment, according to official sources.

It is also worth noting that radioactive waste (RAW) is present in many other regions across our vast country.

Additionally, radioactive waste (RAW) is stored at Rosatom company sites in temporary storage facilities, which also maintain safety conditions. However, the operational lifespan of these facilities (approximately 70 years) is nearing its end. Therefore, it is time to address this issue decisively by creating a fully reliable system for the final isolation of hazardous waste.

Several European countries, including France, Hungary, and Sweden, such facilities have existed for a long time. Some have even been decommissioned and converted into meadows and hills covered with grass.

But this is only a half-measure: a truly reliable disposal site must be underground. In this case, its protection would be ensured not only by engineered systems but also by geological conditions—hundreds of meters of stable, preferably impermeable, rock or clay formations.

Since 2015, such an underground dry storage facility has been in use and is simultaneously under construction in Finland. At Onkalo, high-level radioactive waste (HLW) and spent nuclear fuel (SNF) will be sealed in granite bedrock at a depth of approximately 440 meters, placed in copper canisters further isolated by bentonite clay, ensuring containment for at least 100,000 years. In 2017, Swedish energy company SKB announced that they would adopt this method and construct their own repository near Forsmark. In the United States, debates continue over the construction of the Yucca Mountain repository in the Nevada desert, which would extend hundreds of meters into a volcanic mountain range.

In Russia, after studying the experience of these nations, a new strategy for radioactive waste (RAW) management was also initiated. In 2011, a special law was adopted, and in 2012, a federal unitary state enterprise was established as the sole legally authorized entity responsible for carrying out this work.

The first region to develop next-generation storage facilities was the Middle Urals, where a near-surface disposal facility (NSDF) for Class 3-4 radioactive waste is already operational. In 2022, the second phase was commissioned. The first phase began receiving packaged radioactive waste in 2016 and is now fully filled—its construction was initially started by the Ural Electrochemical Combine (UECC) in Novouralsk before the facility was transferred to

the designated operator. As for the second phase, it is a completely independent project by the National Operator for Radioactive Waste Management (NO RAO), from design to full completion.

A near-surface disposal facility (NSDF) for Class 3-4 radioactive waste is structured as a complex of buildings, including a reception building for transport and packaging containers (TUKs) and an entry control facility, which conducts both radiation monitoring and visual inspections of the containers' condition. The core of the facility consists of massive concrete storage structures divided into cells. A gantry crane lowers the TUKs into these cells after thorough inspections, including spectrometric analysis, ensuring no radiation leaks. Unlike older designs, the concrete structures of the second phase are housed inside hangars rather than being exposed to the open air, allowing waste to be loaded in any weather, year-round. The spaces between containers are filled with inert materials such as bentonite or clay. Once the storage facility is full, the concrete structures will be sealed with a waterproof concrete slab to prevent water infiltration and corrosion of the waste packaging, thereby eliminating the risk of radiation leakage. Finally, the entire facility will be covered with soil and grass will be planted, integrating it into the surrounding landscape.

The experience gained in Novouralsk is aiding in the design and construction of similar facilities elsewhere. Work is already underway in Ozersk (Chelyabinsk region) and Seversk (Tomsk region), with storage capacities of 225,000 and 142,000 cubic meters, respectively. Another facility with a capacity of 200,000 cubic meters is planned for Dimitrovgrad (Ulyanovsk region), though investment justification is still pending. Thus, in a few years, Russia will have four final disposal sites for short-lived radioactive waste, with a total capacity exceeding 620,000 cubic meters. For comparison, the French operator ANDRA's disposal facility in Champagne is designed to store one million cubic meters.

The isolation of liquid radioactive waste (LRW), of which a significant amount is also formed, is done in a completely different way: they are simply pumped into the bowels of the earth, where they will remain until the total attenuation of activity. There are no concrete storage facilities and thick-walled steel barrels here - these are just very deep wells. According to experts, it is completely safe, the waste there is hermetically sealed in special geological formations separated by a water-resistant layer of clay rocks. Thus, the penetration of radiation

into water sources is excluded: the injection depth of LRW is from 250 to 450 meters, while aquifers are no deeper than 50 meters. And, of course, there is constant monitoring of underground storage facilities. For this purpose, observation wells have been created – there are 404 of them on an area of about 32 square kilometers at the Seversk deep injection site (PGZ LRW).

This site was established in 1963 and was managed by the Siberian Chemical Combine (SCC) until 2012. It is now operated by the Federal State Unitary Enterprise “NO RAO.” Over nearly 60 years, there has not been a single emergency, including radiation leaks to the surface, either at this site or at other Russian deep injection facilities for liquid radioactive waste (PGZ LRW). Currently, the underground reservoirs in Seversk are only about one-third full, so plans are in place to extend the facility’s operation until 2033. Additionally, there will be a gradual transition to solidifying liquid waste, vitrifying it, and transferring it to near-surface disposal sites. Other PGZ LRW facilities in Russia follow a similar operational model.

When it comes to the most hazardous radioactive waste—solid Class 1-2 RAW—their disposal requires the most rigorous approach. Although the volume of such waste is relatively small, the costs of final isolation are significantly higher than for other classes. This is reflected in disposal tariffs: for example, in 2022, the state-approved rate for Class 4 RAW disposal was 55,200 rubles per cubic meter, whereas for Class 1 waste, it was nearly 1.57 million rubles per cubic meter.

Currently, there is an insufficient number of storage facilities for Class 1-2 radioactive waste (RAW) both in Russia and worldwide. To address this issue, a repository is being constructed in Krasnoyarsk Krai, in the depths of the Nizhnekansk rock massif, near Zheleznogorsk. The project consists of two phases. The first stage is the construction of a special underground research laboratory, where more than a hundred experiments will be conducted to refute or confirm the feasibility of environmentally safe burial of high- and medium-active long-lived radioactive waste in this area. The second stage is the construction of the storage facility itself. The facility has been under construction since 2018, most of the infrastructure is already ready, in 2022 they began to make the mouths of the ventilation duct, in 2023 they began to drill vertical shafts with a depth of 550 meters (there will be three of them), and then horizontal workings will be drilled into the rock.

If laboratory studies confirm that this method of disposal is safe, the most hazardous radioactive waste will be transported to this site. Vitrified high-level radioactive waste will be placed in special containers and lowered to depths of 450–525 meters into the underground excavations, where they will be sealed for millennia. (3)

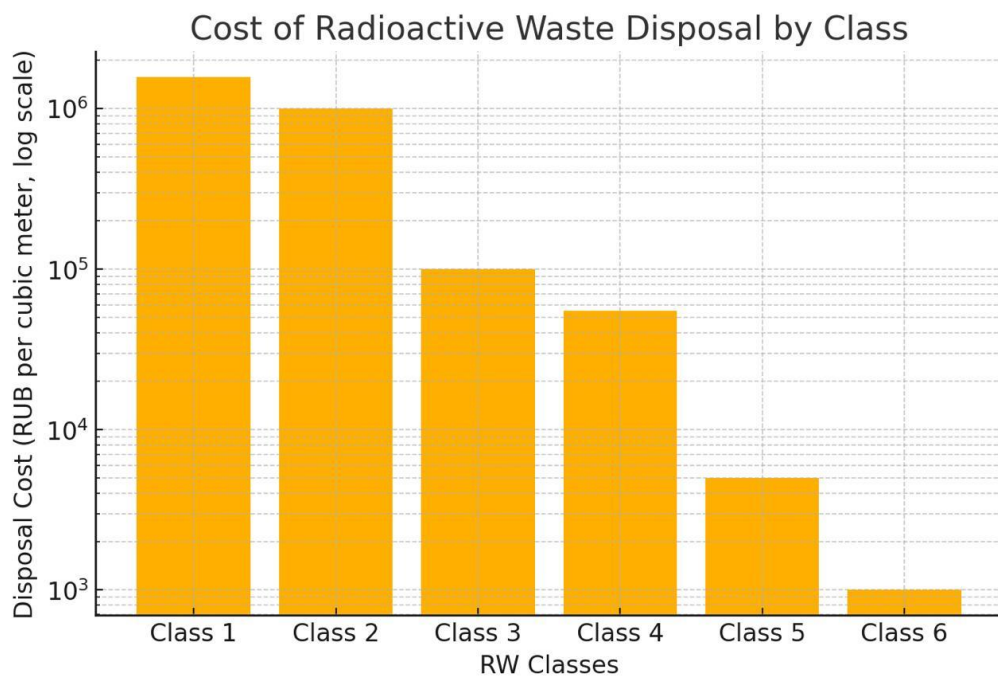
At the same time, one unresolved issue remains: the final decision on the materials for the containers intended for the transportation and storage of radioactive waste (RAW) has not yet been made. This choice depends on several key factors, primarily the material's corrosion resistance, weight, and structural strength.

The relevance of radioactive waste (RAW) disposal and spent nuclear fuel (SNF) management is driven by several key factors that underscore its importance in modern society.

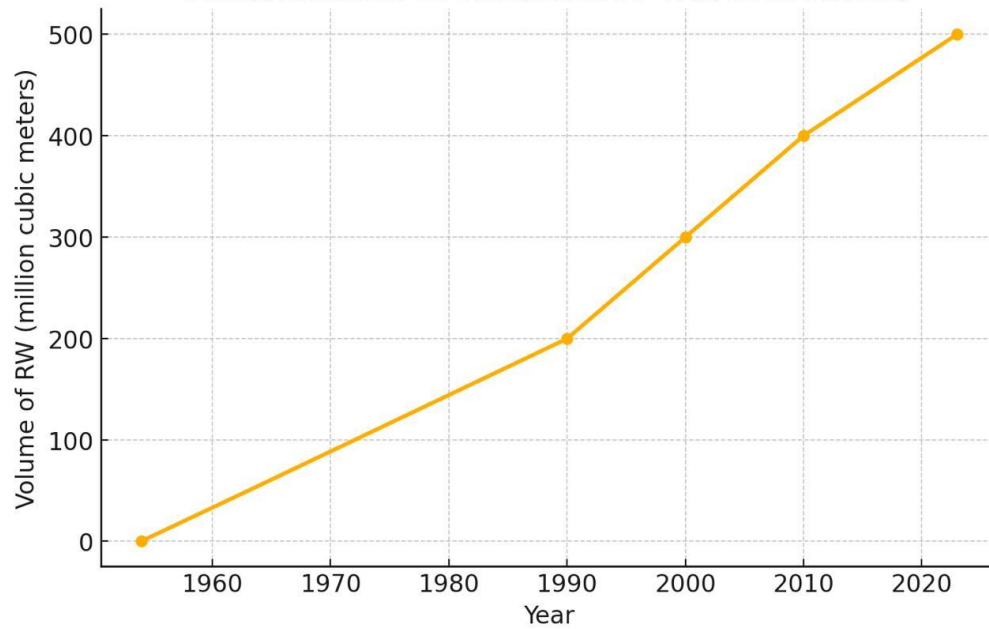
1. **Increasing Energy Consumption:** With global economic growth and rapid technological advancement, the demand for energy continues to rise. Nuclear energy, as one of the key sources of electricity, offers an efficient solution to meet these needs. However, this also brings the challenge of safely and effectively disposing of the resulting waste, making the issue of radioactive waste (RAW) management particularly relevant.
2. **Environmental and Health Risks:** Radioactive waste poses a significant threat to both the environment and human health. Improper handling can lead to contamination of water bodies, soil, and air, potentially causing diseases and long-term ecological damage. The relevance of this issue lies in the need to develop reliable storage and disposal methods that minimize these risks and ensure environmental safety.
3. **Technical and Scientific Challenges:** The management of radioactive waste requires advanced technologies and scientific expertise. Developing efficient methods for processing and safely disposing of RAW is a complex challenge for scientists and engineers. This issue is relevant not only from an environmental perspective but also as a driver of scientific research and technological progress.
4. **Social Perception and Regulatory Framework:** Public opinion on nuclear energy and its waste is often influenced by concerns and skepticism. The need for a transparent radioactive waste management system, along with efforts to educate the public on safety measures, makes this issue crucial for the sustainable development of nuclear

energy. Establishing clear regulations and fostering public trust are essential to ensuring long-term acceptance and responsible handling of nuclear waste.

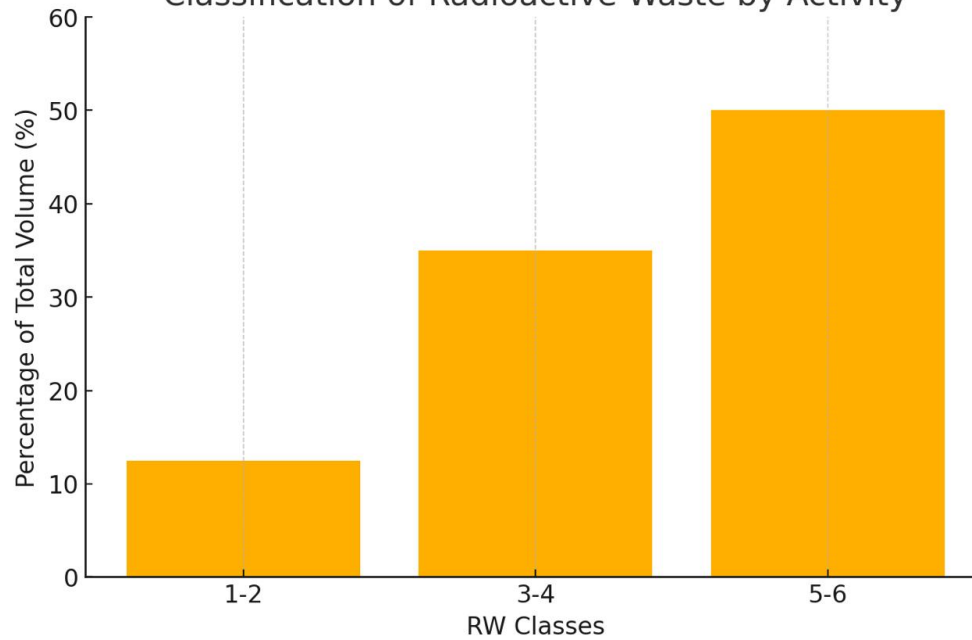
5. International Cooperation and Knowledge Sharing: The issue of radioactive waste disposal is a global challenge. Countries utilizing nuclear energy face similar difficulties, creating opportunities for international collaboration, experience exchange, and the implementation of best practices. The relevance of this topic lies in the necessity of joint efforts at the international level to develop effective and sustainable solutions for radioactive waste management.

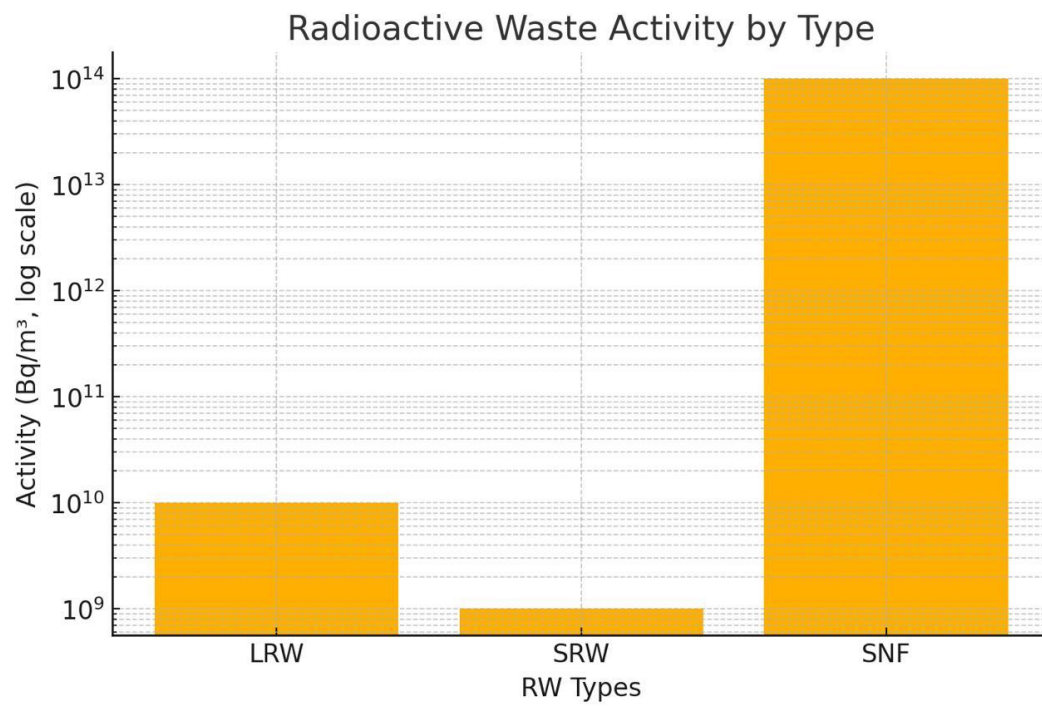
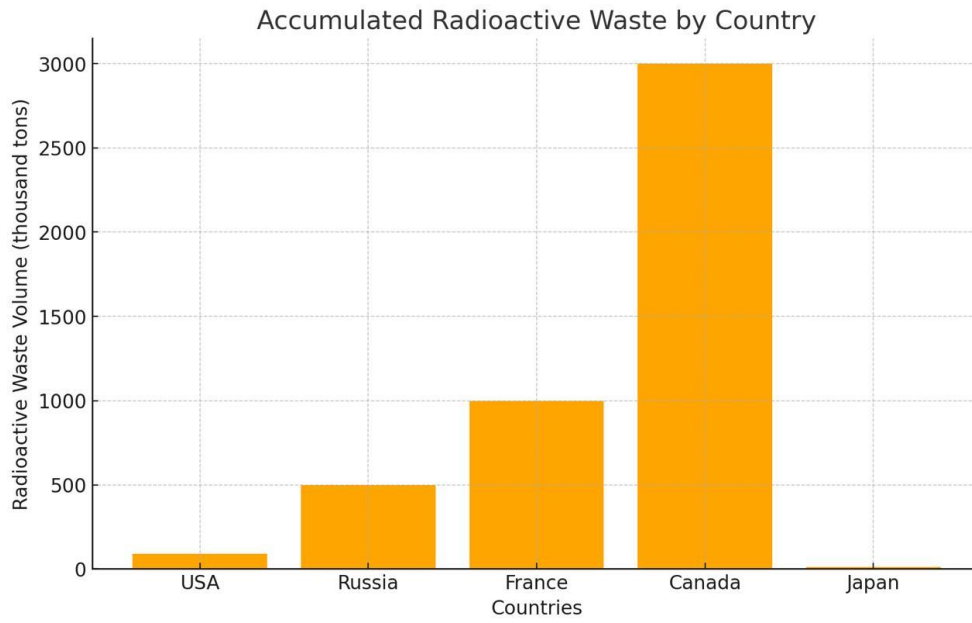


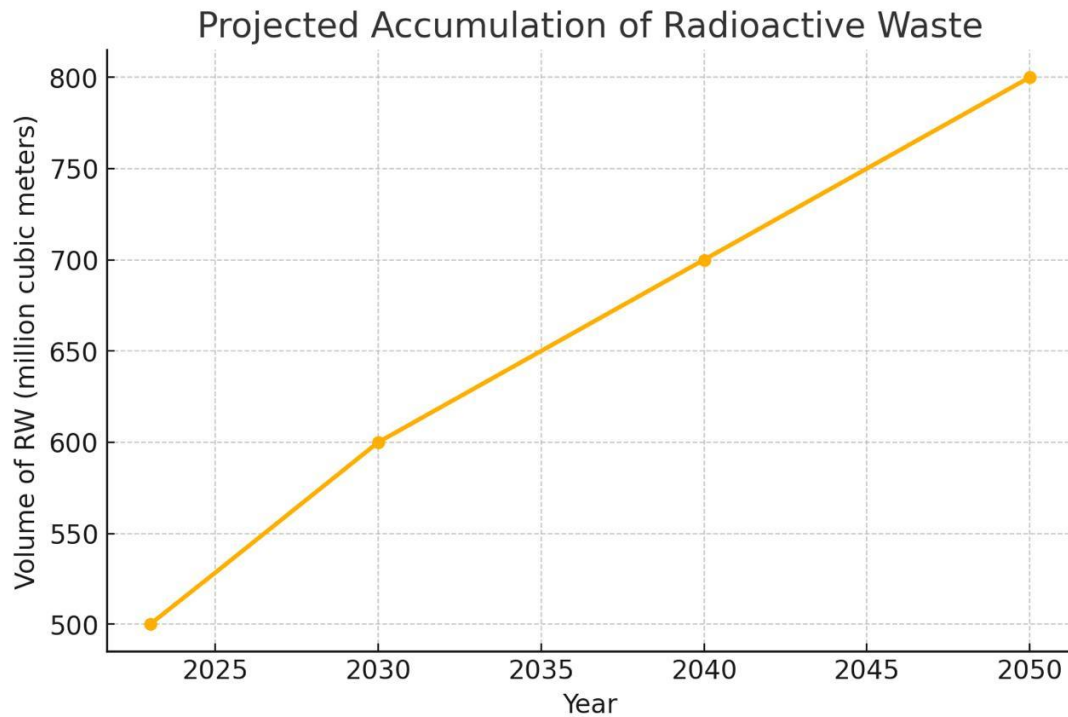
Accumulation of Radioactive Waste in Russia



Classification of Radioactive Waste by Activity







Conclusion:

The key issue remains the lack of effective radioactive waste (RAW) recycling technologies. Instead of developing waste-free processing methods, waste is treated and placed in storage facilities, which require significant resources and occupy large areas. It is crucial to remember that the development of nuclear energy must be accompanied by careful planning and the creation of reliable solutions for the safe disposal of radioactive waste.

The management of radioactive waste (RAW) and spent nuclear fuel (SNF) is one of the most pressing challenges associated with the development of nuclear energy. With the increasing volume of energy production and, consequently, the accumulation of waste, it is essential to develop and implement effective systems for the safe handling of these materials. Improper disposal of RAW can lead to severe environmental and health consequences, highlighting the need for a comprehensive approach to solving this issue.

Modern technologies and scientific research play a key role in developing sustainable solutions for radioactive waste management. The application of various storage and processing methods, along with the adoption of international standards and best practices, can significantly enhance

safety in handling RAW. This is especially relevant in light of growing public concerns and the need for transparency in processes related to nuclear energy.

Despite significant progress in the disposal and storage of radioactive waste, the challenge remains highly complex and requires further investment in research and the development of new technologies. It is crucial for governments and international organizations to collaborate in creating reliable systems that can ensure the safety of both the environment and human health.

In conclusion, effective radioactive waste management is a necessary condition for the sustainable development of nuclear energy. Solving this issue requires a comprehensive approach that incorporates scientific, technical, and social aspects. Only through collaboration and innovation can we hope to create a safe and environmentally sustainable future in nuclear energy.

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Challenges and Future Prospects