International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 1s, 2025
https://www.theaspd.com/ijes.php

Effectiveness of Nuclear Waste Disposal: A Critical Analytical Study

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Abstract: *Using an analytical and critical approach, this study examined the effectiveness of nuclear waste disposal. The findings revealed that nuclear waste poses significant environmental and health risks due to the challenges associated with its safe disposal. One of the most critical threats lies in the potential for such waste to be repurposed for non-peaceful purposes or disposed of through harmful methods such as surface burial or ocean dumping. Currently, there is no optimal method for its disposal, given the large volume of waste and the extended duration of its radioactivity, which may last for millions of years. Moreover, some countries dispose of it unsafely or transfer it to poorer nations, while others send it into space in violation of international agreements.*

The study recommends that nuclear waste disposal be conducted in strict compliance with precise standards and under rigorous supervision. It emphasizes the importance of fully adhering to all safety precautions and procedures to prevent radioactive leaks and protect the surrounding environment. It also calls for coordinated international legal and research efforts to address the challenges of nuclear waste by establishing binding international legislation that enforces best practices and imposes strict penalties for violations.

Keywords: *Nuclear energy, waste, disposal, burial, dumping, incineration.*

INTRODUCTION

The topic of nuclear energy is among the most controversial in modern discourse, rarely has any other issue commanded such significant military, political, and economic attention. On one hand, there are those who believe that the use of nuclear energy—even for commercial purposes—poses a grave threat to public health, safety, and international security due to the dangers of radioactive nuclear waste, including the risk of nuclear weapons proliferation. Humanity's first encounter with nuclear energy and nuclear fission was marked by the United States' detonation of the first atomic bomb over Hiroshima, Japan, in 1945—an event whose consequences remained visible even four decades later. From an economic standpoint, nuclear fission energy has been largely unsuccessful; the rising costs of nuclear reactors, along with their operation and maintenance expenses, continue to increase annually, making electricity generated from this source considerably more expensive compared to other sources. Furthermore, the dangers posed by nuclear waste are far from negligible, especially given that, to date, humanity has not yet discovered a safe and effective method for its disposal (Daees, 1985).

This study addresses the problem of the effectiveness of nuclear waste disposal, given that it is among the most dangerous and complex types of waste. It examines the efficacy of the disposal methods adopted by nuclear states in managing waste from their nuclear reactors.

The study aims to clarify and elaborate on the general concept of waste, with a particular focus on nuclear waste as one of the most hazardous forms. It seeks to explain the types and classifications of nuclear waste. Furthermore, it explores in detail the disposal methods used globally, emphasizing safe and effective approaches to handling nuclear waste, which demands special treatment due to its environmental and health risks. The discussion also covers modern technologies in waste management and disposal, highlighting best global practices in the field.

RESEARCH METHODOLOGY

The research methodology for examining the effectiveness of nuclear waste disposal is based on the use of a deeply analytical approach combined with a comprehensive critical method. These approaches enable a thorough analysis of all aspects related to the effectiveness of nuclear waste disposal processes. The methodology also includes a comprehensive evaluation of the current techniques and practices employed in nuclear waste disposal, with a particular focus on assessing their efficiency and the extent to which they achieve the intended objectives. This ultimately aims to develop a deeper understanding of the overall effectiveness of nuclear waste management.

NUCLEAR ENERGY AND THE RISKS OF ITS WASTE

Since ancient times, humans have sought to understand the mysteries of the universe and the nature of things. Greek civilization and its philosophers played a pivotal role in the development of human thought, among them the philosopher Democritus, who was fascinated by nature and the movement of celestial bodies. He questioned who had set them in motion with such remarkable order, and ultimately concluded that everything in the universe is composed of extremely small, indivisible particles, which he called "atoms" (Perl, 1958). In 1935, uranium-235 was discovered, and in 1938 it was announced that uranium atoms could be split when bombarded with neutrons, releasing a large amount of thermal energy. By 1942, the first self-sustaining nuclear chain reaction in natural uranium had been achieved (Childs, 1981).

Nuclear energy is defined as the energy released during fission or fusion processes that lead to nuclear reactions (Taha, 2000). Some scholars define it specifically as the energy produced by the fission of uranium and plutonium nuclei (Taha, 1986).

Nuclear energy is considered one of the most significant and dangerous discoveries of the 20th century. The future and fate of humanity are closely tied to this powerful source of energy and the manner in which it is used. Nuclear energy has proven to possess two inherently contradictory faces: a dark face that threatens humanity and its civilization when used for military purposes, and a bright face marked by the promise of progress and a better life when applied for peaceful purposes, whether on Earth or in outer space. For this reason, it became necessary to establish an international legal framework to ensure that nuclear energy is used exclusively for peaceful purposes, to prevent its use in warfare, and to dedicate its potential to the service of peace. This necessitates the implementation of effective safeguards and the existence of a rational will to ensure their enforcement and the proper use of nuclear energy for the benefit of humanity (Habib, 2018).

Accordingly, nuclear waste represents one of the most serious and troubling aspects of nuclear energy. It remains among the greatest challenges facing the continued use of nuclear power. These wastes form an integral part of the dark and negative side of nuclear energy due to their long-term environmental and health risks. Furthermore, the issue of safe disposal remains an unresolved dilemma, sparking significant debate and concern among experts and stakeholders in the field.

THE CONCEPT AND TYPES OF NUCLEAR WASTE

Waste in general is defined as the residues and byproducts resulting from industrial, agricultural, and domestic activities, whether solid or liquid (Salama, n.d.). Waste pollution refers to substances that, due to their quantity, concentration, or physical or chemical characteristics, may pose a serious risk to the environment or human health if not properly treated, removed, stored, or transported (Atiyah, 2014). Hazardous waste pollution is among the most threatening types of pollution to the Earth's environment. Consequently, certain legislations—especially European ones—have required authorities to create registries of contaminated sites to be made publicly accessible before any legal action is taken concerning them, particularly given that some hazardous wastes are disposed of via burial or landfilling (Hamidani, 2016).

Nuclear waste is considered a significant source of nuclear damage, as it poses risks no less serious than other sources of nuclear harm. The Saudi Civil Liability for Nuclear Damage Law does not specifically define nuclear waste, but it provides a definition for radioactive products and waste as: any radioactive material produced during the production or use of nuclear fuel, or any material that has become radioactive due to incidental exposure during nuclear fuel production or use. This definition excludes radioactive isotopes that have reached their final manufacturing stage and are ready for use in scientific, medical, agricultural, commercial, or industrial applications.

The Saudi Law on Control of Nuclear and Radiological Uses defines radioactive waste in Article 1 as: materials resulting from activities, practices, or intervention operations such as radiological decontamination, regardless of their physical state, which are not expected to be reused and which contain or are contaminated with radioactive substances, possessing levels of radioactivity exceeding the regulatory release limits.

This definition aligns precisely with that provided in Article 1, paragraph (g) of the Vienna Convention on Civil Liability for Nuclear Damage.

Legal scholars have also defined nuclear waste. It has been described as any unusable material containing or contaminated with radioactive nuclei exceeding permitted levels as defined by the competent authority in each country (Al-Shafei, 2010). Another definition characterizes it as the byproducts of nuclear reactions used in atomic reactors for various purposes, including research and the production of radioactive isotopes for peaceful or military uses, as well as spent radioactive elements (Badr Al-Din, 2005).

In summary, nuclear waste refers to radioactive residues generated from various nuclear applications and activities, whether in solid or gaseous form.

Nuclear or radioactive waste differs from other hazardous waste primarily in origin. While hazardous waste comes from diverse sources and includes highly toxic byproducts of chemical-based industries, nuclear waste arises from nuclear or atomic reactions and is typically generated in large quantities in countries operating nuclear power plants or involved in nuclear military industries (Abd Al-Latif, 2016).

The sources of radioactive nuclear waste vary depending on the type of industrial activity from which the waste originates. These sources include nuclear power plants, stages of the nuclear fuel cycle, the extraction of radioactive ores such as uranium and thorium, and the use of radioactive isotopes in scientific research, industry, agriculture, and nuclear medicine, including diagnostics and therapy (Fath Al-Bab, 2016).

NUCLEAR WASTE IS CLASSIFIED INTO THREE LEVELS

1- High-Level Radioactive Waste (HLW):
These contain highly radioactive materials and remain hazardous for extended periods. They typically result from spent nuclear fuel, considered among the most dangerous types of nuclear waste. Handling requires thick shielding and remote control technologies to avoid human contact and environmental exposure.

2- Intermediate-Level Radioactive Waste (ILW):
This waste contains moderate levels of radioactivity and originates from the use or production of certain radioactive isotopes, reactor operations, and equipment components. It requires protective barriers, special clothing, and storage in vitrified forms to reduce radioactivity before final disposal.

3- Low-Level Radioactive Waste (LLW):
LLW contains weakly radioactive materials with short half-lives that decay quickly. They are typically handled manually with protective gloves and clothing. These wastes primarily originate from the use of radioactive isotopes in medicine, industry, and scientific research (Fath Al-Bab, 2016; Belbali, 2017; Mahdawi, 2014).

The danger of nuclear waste lies in two major aspects: first, its potential for reactivation and use in non-peaceful applications; second, its improper disposal, which poses serious environmental and health risks that may persist for decades (Abd Al-Halim, 2014).

Complete decay of some radioactive substances used in nuclear power generation can take thousands of years. Hence, the nuclear industry presents critical challenges, foremost among them the disposal of spent fuel that remains hazardous for millennia. Some nuclear waste can be permanently discarded, while others may be reusable as fuel after advanced processing and thus require temporary storage. In the United States, the Nuclear Waste Policy Act of 1982, as amended, assigns the Department of Energy responsibility for developing a disposal system. Studies have been conducted on deep geological storage, an approach favored by the U.S., while other ideas include ocean burial, space disposal, or laser treatment—though none are yet completely safe. Surface storage remains feasible but depends heavily on human monitoring and maintenance, rendering it vulnerable to sabotage or terrorism (Abdullah, 1995).

While awaiting the results of intensive research to resolve final disposal issues, countries have designated geologically stable sites for temporary underground storage lasting several years. However, due to the lack of permanent disposal solutions, storing spent fuel at reactor sites may result in premature closure, as was the case in Germany in 2000 (Abdullah, 2010).

EVALUATION OF NUCLEAR WASTE DISPOSAL METHODS

The issue of nuclear waste disposal remains one of the most complex and controversial challenges on the international level. Nations and international organizations concerned with nuclear energy face significant obstacles in developing effective and safe solutions to this problem. The difficulty of disposing of nuclear waste stems from several key factors, most notably the vast quantities generated annually by nuclear reactors, as well as the hazardous nature of the waste, which remains radioactive for extremely long periods—sometimes extending to millions of years. Despite extensive and ongoing research efforts, no optimal method has yet been found to ensure the final disposal of such waste without posing risks to the environment or human health. Additionally, the high costs associated with storing and processing nuclear waste impose further burdens on countries that rely on nuclear energy, making the issue increasingly urgent over time.

Some countries employ unsafe methods to bury nuclear waste in shallow underground depths, or dispose of it by ocean dumping. Others exploit periods of armed conflict to dispose of their waste in poor or developing countries, which have become victims of this hazardous material. Some nations even send their waste into outer space via rockets—despite the fact that such practices violate international treaties reserving outer space for peaceful purposes (Abu Nazel, 2019; Mahdawi, 2009; Zeidan, 2014; Fadel, 1976).

In response, international efforts have turned to scientific and practical methods such as deep geological disposal in remote areas far from population centers, or ocean floor dumping. Although the latter is technically acceptable due to the vastness of the oceans, increasing levels of dumping have led to growing impacts on marine life and, indirectly, on humans. Incineration is also used in some cases to convert radioactive waste into ash that is less harmful or non-harmful (Ahmed, 2016).

In all cases, nuclear waste disposal—whether through deep geological burial, ocean dumping, or incineration in specialized facilities—must be carried out according to precise standards and under strict supervision. Full compliance with safety precautions and protocols is essential to prevent radioactive leaks and environmental contamination. Despite the widespread use of traditional disposal methods, they remain a source of concern for scientists and experts due to their potentially severe long-term impacts on public health and environmental stability—even if such effects only emerge decades or centuries later.

Therefore, it is essential to strengthen international cooperation to address this critical challenge by intensifying joint efforts in scientific research and technological development to achieve safer and more effective waste management solutions. It is also necessary to establish binding international legislation to ensure the application of best practices, and to impose strong penalties for non-compliance. Moreover, adequate resources must be allocated for the continuous monitoring and supervision of waste disposal activities to prevent harm to humans, living organisms, and the entire ecosystem.

FINDINGS

The findings of the study on the effectiveness of nuclear waste disposal can be summarized as follows:

1. Nuclear waste represents one of the darker aspects of nuclear energy due to its long-term environmental and health risks.
2. The danger of nuclear waste lies in two key areas: first, the potential for its reactivation and reuse in non-peaceful applications; second, its unsafe disposal, which poses threats to environmental, health, and public safety.
3. Multiple challenges surround nuclear waste disposal on the international level, as scientific research has yet to identify an optimal method for its safe elimination, given its massive volume and extremely long radioactive lifespan.
4. Some countries continue to use unsafe disposal methods, such as shallow burial, ocean dumping, or exploitation of conflict zones in poorer countries. Others send waste into space, despite the violation of international agreements.

RECOMMENDATIONS

Based on the findings of this study on the effectiveness of nuclear waste disposal, the following recommendations are proposed:

1. Nuclear waste disposal must be carried out in accordance with strict standards and under rigorous supervision, ensuring full compliance with safety measures to prevent radioactive leakage and environmental contamination.
2. International efforts should be unified to reduce the challenges posed by nuclear and radioactive waste.
3. Joint efforts in scientific research and technological development should be intensified to achieve safer and more effective nuclear waste management solutions.
4. Binding international legislation must be enacted to ensure the implementation of best practices in nuclear waste disposal, along with strict penalties for violations.
5. Adequate resources should be allocated for the continuous monitoring and oversight of nuclear waste disposal operations to prevent potential harm to humans, living organisms, and the ecosystem at large.

ACKNOWLEDGMENT

The authors are thankful to the Deanship of Graduate Studies and Scientific Research at Najran University for funding this work under the Growth Funding Program grant code (NU/GP/SEHRC/13/121-3)

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