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Review and Perspective on Intermediate Depth Disposal of Radioactive Solid Waste in China

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Abstract. This article provides an overview of the research and development status of medium-depth disposal in selected foreign countries and summarizes the research progress in China's medium-depth disposal. Medium depth disposal of radioactive solid waste is the systematic project, and the technique of it is complex, and the influencing factors are various. This article summarizes the status of Medium depth disposals in Sweden, Finland, and Korea. The research status of Medium depth disposal in CHINA, containing the source term, concept study and technological process, and safety case, is put forward. The urgent scientific and technological problems of Medium depth disposal in CHINA, including the source term, site survey, key technologies of overall design, safety case, and standard system, are proposed. This article aims to arouse people to pay a full attention on the research and development of Medium depth disposal, and the study could provide technical reference and suggestions to the follow-up research on Medium depth disposal.

Keywords. Medium depth disposal, source term, concept study, safety case

1. Introduction

China follows the relevant requirements of the International Atomic Energy Agency (IAEA) safety guidelines and draws on the advanced experience of foreign disposal engineering practices to implement classified management and disposal of radioactive waste, with the "ultimate long-term safe disposal" as the core and ultimate goal of radioactive waste management. In 2017, the Ministry of Ecology and Environment (formerly the Ministry of Environmental Protection), the Ministry of Industry and Information Technology, and the State Administration of Science, Technology, and Industry for National Defense jointly issued the "Classification of Radioactive Waste" (Announcement No. 65 of 2017) [1], which clearly stipulates the applicable disposal strategies and forms for various types of radioactive waste:

- Low-level radioactive waste is subject to near-surface disposal, generally from the surface to a depth of 30 meters underground;
- Medium-level radioactive waste is subject to medium-depth disposal, requiring a higher degree of containment and isolation measures than near-

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surface disposal, with a disposal depth typically ranging from tens to hundreds of meters underground;

- High-level radioactive waste is subject to deep geological disposal, requiring an even higher degree of containment and isolation measures, typically at a depth of 400 to 1,000 meters below the surface.

In 2018, the "Nuclear Safety Law of the People's Republic of China" (Presidential Order No. 73) was promulgated and implemented, with Article 40 stating that low- and medium-level radioactive waste shall be disposed of near the surface or at medium depths in facilities that meet national nuclear safety requirements, while high-level radioactive waste shall be subject to centralized deep geological disposal. By now, China has clearly stipulated the disposal forms and requirements for low, medium, and high-level radioactive waste at both the national legal and industry management levels.

As mentioned earlier, the disposal method for medium-level radioactive waste (MLW) is "medium-depth disposal," typically occurring at depths ranging from tens to hundreds of meters below the surface. Its containment and isolation capabilities fall between those of "near-surface disposal" and "deep geological disposal," with project costs also positioned in the middle range. Therefore, the introduction of "medium-depth disposal" for MLW in China in 2017 aims to achieve a "reasonable balance" between "safety" and "economy," which is a necessary requirement for the high-quality economic and social development as well as the efficient and green sustainable development of the ecological environment in our country.

This article provides an overview of the research and development status of medium-depth disposal in selected foreign countries and summarizes the research progress in China's medium-depth disposal. By highlighting the urgent scientific and technological issues that need to be addressed in China's medium-depth disposal, the article aims to accelerate the research and development, as well as the construction of medium-depth disposal projects domestically. Additionally, it offers technical references and suggestions for the subsequent research and development of medium-depth disposal in China.

2. Current Research Status of Medium-depth Disposal Abroad

Currently, there are no dedicated and standalone medium-depth disposal facilities specifically for medium-level radioactive waste (MLW) internationally. However, some countries have built and are operating underground disposal repositories that fall within the category of "medium-depth disposal" in terms of disposal depth. Examples include the SFR repository in Sweden, the Olkiluoto repository in Finland, the Loviisa repository in Finland, and the Wolchong repository in Korea.

2.1. Sweden

The Swedish SFR repository (Phase I) [2-4] is located approximately 60 meters below the seabed of the Baltic Sea, within a granite formation (figure 1). It serves as the final disposal facility for short-lived radioactive waste in Sweden, primarily receiving and disposing of low- and medium-level radioactive waste generated by nuclear power and nuclear technology applications. The repository comprises four disposal tunnels and a concrete silo. It began operations and receiving waste in 1988.

In the disposal tunnels (figure 2) of the SFR repository, the containment and isolation of radioactive waste are achieved through a combination of engineered barriers such as disposal containers, cement mortar between containers, and concrete cells, as well as natural barriers. During operation, radioactive waste is placed in a regular pattern within the concrete cells using remote-controlled cranes. When the tunnel is closed, the remaining space within the disposal tunnel is backfilled with materials such as gravel.

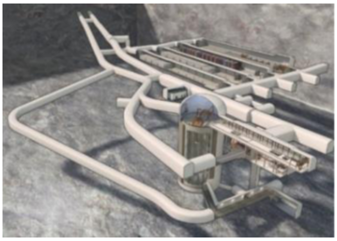

Figure 1. 3D diagram of the Swedish SFR repository (Phase I).

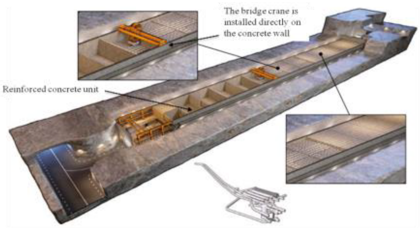

Figure 2. Schematic diagram of tunnel disposal within the Swedish SFR repository.

For silo-type disposal (Figure 3), the containment and isolation of radioactive waste are achieved through a combination of engineered barriers such as disposal containers, cement mortar, silo walls (partitions), concrete cylindrical walls, and bentonite, as well as natural barriers. Compared to tunnel-type disposal (Figure 2), the silo structure is relatively complex, and the design process faces greater difficulties and challenges. During operation, radioactive waste is placed in a regular pattern within the silo's vertical shafts using remote-controlled cranes located at the top of the silo. When the silo is closed, the remaining upper space within the silo is backfilled with materials such as compacted bentonite.

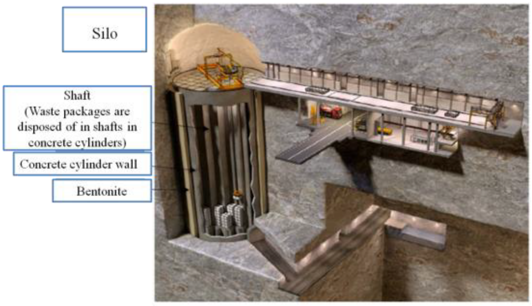

Figure 3. Schematic diagram of silo disposal within the Swedish SFR repository.

2.2. Finland

The Olkiluoto repository in Finland [5-6] is located approximately 70-100 meters below the seabed of the Baltic Sea along the southwestern coast of Finland, within a granite formation (figure 4). It primarily disposes of low- and medium-level radioactive waste generated by the two boiling water reactors at the Olkiluoto nuclear power plant.

The repository is being constructed in phases, with the first phase involving the construction of two concrete silos. The repository began operations in 1992.

Currently, the two silos are used separately for the disposal of low-level radioactive waste and medium-level radioactive waste (figure 4). For the silo dedicated to medium-level waste, an additional layer of concrete wall has been added compared to the silo for low-level waste, serving as an engineered barrier to slow down the release of radionuclides. During operation, radioactive waste is placed in a regular pattern within the silo using numerically controlled cranes (figure 5).

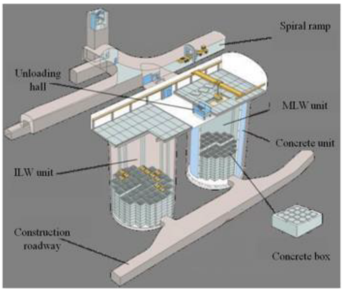

Figure 4. Schematic diagram of the Olkiluoto repository in Finland.

Figure 5. On-site photograph of the unloading hall in the Olkiluoto repository.

2.3. Korea

The Wolchong repository in Korea [7-9] is located in a mountainous area near the Wolchong Nuclear Power Plant in the southeastern part of the country. The repository is situated within granite formations at a depth of 80-130 meters below the surface (figure 6). It primarily receives and disposes of low- and medium-level radioactive waste generated by nuclear power operations. In 2014, the first phase of the project was completed with the construction of six disposal silos.

The radioactive waste disposed of within the silos is contained and isolated through a combination of engineered barriers and natural barriers. Additionally, in the closure design, different buffer backfill designs are employed for different functional areas (figure 7). For construction tunnels, unloading tunnels, and the upper space of the silos, crushed rock is used for backfilling to maintain the long-term stability of the caverns. The connection between the unloading tunnel and the silo, which is a vulnerable area affecting containment and isolation performance, is sealed with a concrete plug (enhanced engineered barrier) to minimize the ingress of groundwater.

In summary, international experience in the design and operation of rock cavern-type repositories for low- and medium-level radioactive waste (tunnel-type and silo-type) can provide important insights and valuable references for the overall engineering design and feasibility of medium-depth disposal in China. However, it is crucial to note that waste generation and management strategies vary among countries, leading to significant characteristics and differences in the overall design of disposal projects. Therefore, there are no universal technical standards or engineered solutions for medium-depth disposal.

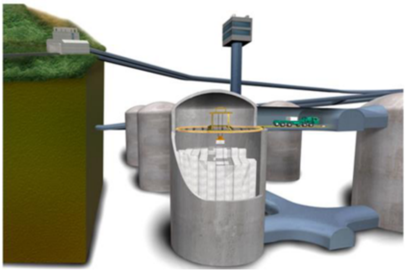

Figure 6. Schematic diagram of the Wolchong repository in South Korea.

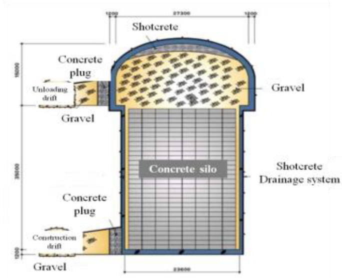

Figure 7. Schematic diagram of the Wolchong repository after closure.

3. Research Progress of Medium-Depth Disposal in China

In 2019, China's first research project on medium-depth disposal, titled "Preliminary Research on Medium-Depth Disposal of Radioactive Waste (Top-Level Design Phase)," received approval [10]. Through this research, a preliminary understanding of the classification of waste sources for medium-depth disposal in China was achieved. Additionally, initial proposals for the technical route and engineered barriers for medium-depth disposal were formulated. The research also made progress in the top-level design phase by conducting studies on safety strategies and safety goals for medium-depth disposal, and preliminary frameworks for the top-level design and legal mechanisms related to medium-depth disposal were outlined.

3.1. Waste Source Term Investigation for Medium-Depth Disposal

Currently, based on the definition of Medium-level radioactive waste in the "Classification of Radioactive Waste" (Announcement No. 65 of 2017) [1], China has investigated and analyzed the waste sources intended for medium-depth disposal, taking into account the safety requirements of disposal facilities. Further classification and categorization have been conducted for waste radioactive sources, solidified waste from Medium-level liquid waste near the upper limit, reactor core wastes, graphite wastes from high-temperature gas-cooled reactors, wastes generated by nuclear power plants and reprocessing plants, and other wastes. This process has clarified the scope of radioactive waste sources that require medium-depth disposal (e.g., reactor internals, filter cartridges, etc. generated during nuclear facility operation and decommissioning). Preliminary estimates indicate that the total volume of waste requiring medium-depth disposal in the future is approximately 120,000 cubic meters.

3.2. Concept and Process Flow of Medium-Depth Disposal

The design of the conceptual scheme for medium-depth disposal facilities is closely related to factors such as radioactive waste source terms, site conditions, retrievability of waste, and safety evaluations. Currently, based on China's near-surface disposal plans and the conceptual design of high-level radioactive waste repositories, as well as the technical capabilities and levels of domestic waste disposal engineering-related fields (e.g., tunneling engineering), three possible conceptual design schemes for medium-depth disposal in China have been proposed, tailored to the characteristics of the waste sources intended for medium-depth disposal:

- Concrete-based Disposal Concept: This scheme involves using a significant amount of low-permeability concrete and other cement-based materials to restrict groundwater flow through the waste, thereby limiting the diffusion and transport of radioactive waste to the external environment.
- Clay-based Repository Concept: This scheme employs large quantities of low-permeability and highly adsorbent bentonitic clay to encapsulate long-lived Medium-level radioactive waste, achieving retardation of radioactive waste.
- Gravel-based Repository Concept: This scheme creates a highly hydraulically conductive (permeable) disposal environment to enable rapid drainage of surrounding groundwater, thereby achieving retardation of radioactive waste.

For each conceptual scheme, potential design elements for the construction, operation, backfilling and sealing, and post-closure phases have been analyzed. Additionally, process flows have been proposed for waste package receipt, inspection, repackaging (if needed), transfer of disposal containers, grouting of disposal tunnels, backfilling, and repository closure.

3.3. The Safety Case of Medium-depth Disposal

The Safety Case permeates the entire lifecycle of the disposal facility, encompassing site selection, design, construction, operation, closure, and post-closure monitoring and inspection. For each stage, relevant safety and environmental analysis and justification are carried out in accordance with laws and regulations, with the resulting technical documentation being integrated. This includes: the background of the Safety Case, safety strategies, description of the disposal system, safety assessments, iterations and design optimizations, uncertainty management, limits, controls, conditions, and integration of safety arguments [11]. Currently, based on the work of the "Preliminary Research on Medium-Depth Disposal of Radioactive Waste (Top-Level Design Phase)," research has been conducted on the safety objectives and requirements for China's medium-depth disposal of radioactive waste. An initial proposal has been made to set the risk value for China's medium-depth disposal at the order of 10^-6/a. Additionally, research efforts have been undertaken to conduct uncertainty analysis using methods such as Monte Carlo simulations and Latin Hypercube Sampling.

4. Prospects for Medium-Depth Disposal in China

Currently, China has accumulated extensive practical experience in near-surface disposal projects for low-level radioactive waste, with the overall design technology for disposal sites being relatively mature [12]. Multiple near-surface disposal sites have been constructed and are operational. The deep geological disposal projects for high-level radioactive waste are currently in the stage of underground laboratory construction, with plans to complete the construction of a high-level waste disposal repository by the middle of this century. At this stage, China's engineering research and development efforts in the field of medium-depth disposal are severely inadequate.

Regardless of the accumulation of preliminary technical achievements or existing research investments, the area of medium-depth disposal for Medium-level radioactive waste is still in its initial stages, and numerous research and design efforts remain to be continuously strengthened and intensified.

4.1. Waste Source Term Investigation for Medium-Depth Disposal

The source term characteristics of Medium-level radioactive waste serve as crucial prerequisites for numerous research and design endeavors, directly influencing the conceptual design scheme of the disposal repository and the credibility of safety assessments. Currently, China has initiated preliminary investigations into source terms, yet the depth of these studies needs further enhancement, encompassing: (a) the quantity of Medium-level radioactive waste; (b) radiological characteristics (such as radionuclide composition, half-lives, activity concentrations of radionuclides, surface dose rates, and heat release), along with the determination of the key radionuclide composition in Medium-level radioactive waste; (c) other physical properties (e.g., dimensions, weight, compressibility); (d) chemical properties (including the chemical composition of radioactive waste, water content, solubility, corrosivity, flammability, gas evolution, and chemical toxicity); and (e) biological properties (such as biological hazards associated with the waste).

4.2. Site Studies for Medium-Depth Disposal

As a natural barrier for Medium-level radioactive waste, the medium-depth disposal site also directly impacts the conceptual design scheme and safety assessments. In the site selection process, a comprehensive approach should be taken to identify a site that is safe and reliable, environmentally compatible, technically feasible, and economically reasonable. Currently, the China National Nuclear Corporation (CNNC) has issued the enterprise standard "Technical Requirements for Site Selection of Medium-Depth Disposal Facilities for Radioactive Waste" (Q/CNNC JD 67-2023). However, the specific location for the medium-depth disposal repository has not yet been finalized. It is recommended that further research be conducted on the site selection strategies and criteria for medium-depth disposal facilities for radioactive waste, accompanied by detailed site investigations to determine the potential site conditions (such as public acceptance, degree of joint and fissure development, groundwater conditions, chemical environment, scalability, etc.).

4.3. Research on Key Technologies for the Overall Design of Medium-Depth Disposal

Accurately striking a "reasonable balance" between "safety" and "economy" in the medium-depth disposal of Medium-level radioactive waste represents a critical technical challenge and difficulty in the research and development process. However, this issue remains unresolved as of now, primarily due to the severe lack of in-depth engineering research and development in the field of medium-depth disposal in China, which is still in its initial stages. It is recommended that comprehensive, systematic, and in-depth overall design work be carried out subsequently, encompassing the barrier system of the medium-depth disposal repository (engineering barrier + natural barrier), the layout plan for the sub-projects of the disposal repository, the entire disposal process flow of the disposal repository, and the design of key disposal machinery and equipment.

4.4. Safety Case of Medium-Depth Disposal

The safety strategy for medium-depth disposal is the primary task in the research and development of disposal engineering, and the overall safety of the disposal system depends on the combined effects of various individual barriers. One of the urgent problems to be solved at present is how to determine the roles played by the various engineering barriers (such as disposal containers, backfill materials, disposal tunnels, etc.) and natural barriers in the entire disposal process, and to provide the appropriate proportions of safety weights for different barriers.

4.5. Standard System for Medium-Depth Disposal

Currently, in China, the implementation of medium-depth disposal relies solely on top-level regulatory documents such as the "Law of the People's Republic of China on the Prevention and Control of Radioactive Pollution," the "Nuclear Safety Law of the People's Republic of China," and the "Classification of Radioactive Waste" (Announcement No. 65, 2017). However, specific standards related to the acceptance of Medium-level radioactive waste for medium-depth disposal, the engineering design of medium-depth disposal, and safety aspects of medium-depth disposal have yet to be established. The absence of these relevant standards leaves the design, construction, operation, and evaluation of medium-depth disposal lacking normative standard documents, which will hinder the rapid progress of the overall project implementation. Therefore, it is essential to establish a comprehensive, systematic, suitable, and implementable standard system for medium-depth disposal and to complete the compilation and issuance of urgently needed standards. This is a prerequisite for effectively advancing the implementation of China's medium-depth disposal project for Medium-level radioactive waste.

5. Conclusion

This article provides an overview of the current research and development status in medium-depth disposal in selected foreign countries (Sweden, Finland, and South Korea). It also presents the progress made in China in areas such as waste source term investigations, disposal concepts and processes, and the Safety Case of medium-depth disposal, etc. Furthermore, the article highlights the urgent scientific and technological issues that need to be addressed in China regarding waste source term investigations, site studies, key technologies for overall design, comprehensive safety system analysis, and standard systems for medium-depth disposal. The aim is to draw domestic attention to the importance of research and development in medium-depth disposal and to provide technical references and recommendations for future research and development efforts in this field in China.

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