Analysis Methods for the Uncertainty of Costs in Spent Nuclear Fuel Disposal Systems

K.L. Lee [a*], J. Y. Lee [a], H.J. Choi [a], D.K. Cho [a]
[a]*Korea Atomic Energy Research Institute, Daedeok-daero 989-111,Daejeon,Republic of Korea*
[*]*Corresponding author: kllee@kaeri.re.kr*

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1. Introduction

The Korea Atomic Energy Research Institute (KAERI) is actively engaged in research related to the storage and disposal of domestically produced spent nuclear fuel. In terms of improving the efficiency of the disposal system, there is a need to conduct preliminary assessment of the construction costs for the alternative disposal systems. To analyze disposal costs, it is essential to first define the components of the disposal system and uncertain cost factors.

2. Domestic and International Situation

Almost all countries with commercial nuclear power production are planning to isolate the waste byproduct of their nuclear fuel cycle in a deep geological repository.

The China National Nuclear Corporation (CNNC) is responsible for the development of a deep geological repository for used CANDU fuel, and for high-level waste from the reprocessing of used light water reactor fuel. China's site selection process, which is technically-driven, began in 1986 and focused on three candidate locations in the Beishan region of Gansu province in northwest China. In 2016, one of the siting regions was selected to host an underground research laboratory. The site for the underground research laboratory has strong potential to become the eventual site of the repository. Site selection is expected in the 2020s.

In Finland, Posiva is responsible for the final disposal of the used nuclear fuel of its two owners: Teollisuuden Voima and Fortum Power & Heat. These companies currently operate 4 nuclear reactors, with a fifth expected to start commercial operation in Dec 2022. Posiva's site selection process, which was technically-driven and consent-based, began in the 1980s. In 2000, the Olkiluoto island in Eurajoki was selected as the site for final disposal. The construction licence application for the repository was submitted in 2012 and granted in 2015. An application for a licence to operate was submitted in 2021. Construction is in progress and the excavation of the first five disposal tunnels was completed in June 2022. Civil construction of the fuel encapsulation facility was completed in May 2022 and installation of equipment is currently in progress. Operation is expected to begin in 2023.

In France, Andra is responsible for the long-term management of France's used nuclear fuel. France currently has 59 operational nuclear power plants, with 78 per cent of its electricity coming from nuclear power. Andra's siting studies began in 2007, just outside the village of Bure in the Champagne-Ardenne region of eastern France. In 2023, Andra submitted a licence application for the construction of a deep geological repository. Construction is expected to start in 2025.

Germany's Federal Office for Radiation Protection (BfS) is responsible for the safety and protection of people and the environment against damages due to ionizing and non-ionizing radiation. This includes radiation from sources such as medical diagnostics, mobile communications and nuclear technology. Germany is investigating a site for a deep geological repository, with its procedure outlined in the StandAG (Repository Site Selection Act). The Bundesgesellschaft für Endlagerung (BGE) is the implementing organization. In 2020, as part of the site selection process, the BGE published its interim report on sub-areas. The interim report is subject to public participation and review, which was initiated in October 2020. The former reference repository site at Gorleben is no longer being considered. The final siting criteria are currently being developed.

In Japan, Nuclear Waste Management Organization of Japan (NUMO) is responsible for ensuring the safe, long-term management of vitrified high-level and long-lived intermediate-level radioactive wastes (the latter is termed TRU waste in Japan) from Japan's nuclear fuel cycle. The research and development for geological disposal of these wastes is supported by relevant organizations, including the Japan Atomic Energy Agency (JAEA), which is operating off-site underground research laboratories in both crystalline rock and sedimentary rock.

In CANADA, NUMO has been promoting the siting process since its establishment in 2000. After the great Tohoku earthquake and Fukushima Daiichi accident, a range of discussions were held to reconstruct the geological disposal program at the government level. The Basic Policy Plan according to the Designated Radioactive Waste Final Disposal Act was amended in May 2015. This included a siting strategy in which the Government of Japan will play a proactive role by nominating "scientifically favourable areas" to assist in resolving the issue of high-level radioactive and TRU waste disposal. In addition, there is a plan to help regional populations, and the Japanese public as a whole, to understand the geological disposal program. A detailed geological map, including exclusion areas, was released in 2017 for public review and discussion. NUMO expects site selection by about 2025, with repository operation from about 2035.

In Sweden, The Swedish Nuclear Fuel and Waste Management Company (SKB) was established in the 1970s to manage Swedish spent nuclear fuel and radioactive waste in a safe way. Sweden currently has six operational nuclear power plants, with roughly 40 per cent of its electricity coming from nuclear power. SKB's siting process for a used fuel repository began in the early 1990s. In 2009, after years of feasibility studies, Oskarshamn was chosen as the host municipality of the interim storage facility and encapsulation facility, and the Forsmark site in Östhammar was selected as the host municipality of the final repository. In 2011, SKB applied for a deep geological repository construction licence. On Aug. 26, 2021, the Swedish government approved the application for an increased storage licence for the interim storage facility in Oskarshamn. This aspect is with the Swedish Radiation Safety Authority and the Land and Environment Court for further examination. In 2022, SKB received approval from the government regarding the encapsulation facility in Oskarshamn and the final repository in Östhammar. The Swedish Radiation Safety Authority had also stated its firm support for the suggested solution. Oskarshamn and Östhammar have officially accepted the establishment of the encapsulation plant and final repository in their respective municipalities.

In Switzerland, Nagra is responsible for the safe management of Switzerland's used nuclear fuel. It also engages in co-operative research with other national nuclear waste management organizations around the globe. Switzerland currently has five operational nuclear power plants, with 40 per cent of its electricity coming from nuclear power. Nagra's siting process began in 1972. Zürcher Weinland was originally identified as a potential siting region. However, in 2005 the Swiss government requested that Nagra identify alternative regions. In 2007, the Swiss Federal Office of Energy issued a "Sectoral Plan for Geological Repositories" for public review. The Swiss Federal Council approved the strategic part of the plan. At the end of 2018, after a period of public consultation, Nagra officially entered the last stage of their site selection process, with detailed site investigations of three siting regions. Nagra announced in 2022 that Switzerland's used nuclear fuel will be stored for the long term at Nördlich Lägern, which is located north of Zurich. It expects to submit a general licence application by 2024.

In United States, The Department of Energy (DOE) is dedicated to the safe disposal of waste, including the safe and efficient management of spent nuclear fuel for disposal in a geological repository. The United States currently has 104 operational nuclear power plants, with 19 per cent of its electricity coming from nuclear power. The DOE engaged in the screening of nine candidate sites from 1983 to 1986. In 1987, Congress directed it to study only one site, Yucca Mountain, located near a nuclear weapons test site in Nevada. In 2002, the Secretary of Energy recommended Yucca Mountain to the President. While the President approved the site, the State of Nevada strongly opposed it. In 2009, the government indicated that Yucca Mountain was no longer an option. A Blue Ribbon Commission was formed to provide recommendations for developing a safe, long-term method to manage nuclear waste. In 2013, the Administration issued its Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste, a framework for moving toward a sustainable program for managing the country's used fuel. A new siting process labelled "consent-based siting" was being developed by the DOE. However, that project was cancelled by the 2017-2020 federal administration, and attempts were made to revive the Yucca Mountain project. The current federal administration is reviewing options and developing a new plan.

In South Korea, The Korea Radioactive Waste Agency (KORAD) is responsible for the implementation of South Korea's radioactive waste disposal program. Legislation defining a site selection process, including community consultations, is under preparation. Currently, all used fuel is stored at the reactor sites pending a future government decision on its disposition, which may include either reprocessing or direct disposal. A review committee for spent fuel management policy has been formed with the task of collecting industry and public opinions and recommending policy updates to the government. Research has been ongoing since the 1990s into the development of a geologic disposal concept for high-level waste and spent fuel. The KAERI Underground Research Tunnel (KURT) at Daejeon in a granite host rock has been in operation since 2007, and the Korea Reference Disposal System (KRS) is based on the Swedish KBS-3V concept. A future site-specific underground research laboratory is planned for the chosen deep geological repository site. For planning purposes, the in-service date is assumed to be in 2060.

3. Analysis Methods

3.1 Alternative Disposal Systems

A multi-layer disposal concept is selected as an alternative disposal system according to the evaluation results of experts. The engineering barrier is designed for the PWR/CANDU based on the amount of spent nuclear fuel generated according to the 2nd High-Level Waste National Management Basic Plan. The disposal container to be placed in the disposal hole and the bentonite buffer block installed around it are designed. The structural integrity of the disposal container is evaluated considering the load of the disposal depth environment.

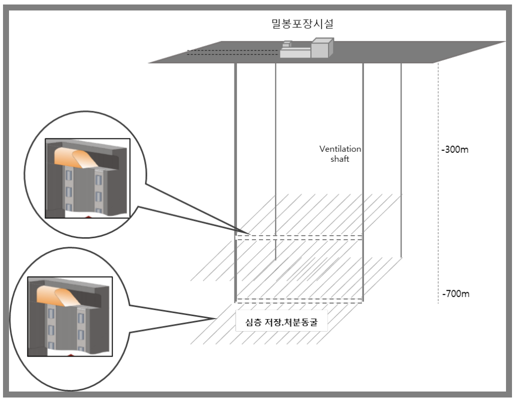

Fig. 1. Multi-layer disposal system.

3.2 Disposal Costs

A. Disposal System

The cost evaluation for permanent disposal of spent nuclear fuel, which represents the final stage of spent nuclear fuel management, is divided into surface facilities and underground facilities.

Notably, the disposal canister cost is included in the surface facility operation costs, while the buffer material cost is included in the underground facility operation costs. The essential input data for disposal cost evaluation are presented as follows;

Surface Facility
Investment Costs:
Design and project management
Construction
Spent nuclear fuel handling system
Process systems
Automation and remote communication systems
Electrical and utility systems
Operation Costs:
Personnel costs
Energy
Water and treatment systems
Maintenance systems
Packaging processes/materials (disposal canisters)
Indirect costs (insurance, etc.)
Operational period
Decommissioning Costs:
Decommissioning design
Personnel costs
Decommissioning waste packaging
Special equipment
Utility costs (water, energy, etc.)
Indirect costs (insurance, etc.)

Underground Facility
Investment Costs:
Surface-linked facilities
Excavation and facility construction
Disposal tunnel construction
Disposal cavern construction
Ventilation, piping systems, etc.
Electrical systems
Process equipment
Investigation/survey systems
Management costs
Contingency funds
Operating Costs:
Backfilling of disposal tunnels
Bentonite blocks (buffer material)
Plugging of disposal tunnels
Personnel costs
Energy expenses
Water supply and treatment
Maintenance
Indirect costs (insurance, etc.)
Investigation/survey expenses
Management costs
Contingency funds
Operational period
Closure Costs:
Structure dismantling
Backfilling of tunnels
Backfilling of shafts
Plugging of shafts and access tunnels
Bentonite plugging of shafts and access tunnels
Management costs
Contingency funds

3.3 Uncertain Cost Factor

These uncertain cost factors fall into four main categories: system uncertainty, scenario uncertainty, model uncertainty, and input variable uncertainty.

- System Uncertainty: Refers to the potential cost variations resulting from changes in disposal system components (such as disposal depth, engineering barriers, etc.). Analyzing how these variations affect disposal costs is essential.
- Scenario Uncertainty: By exploring cost diversities resulting from different disposal scenarios, we can identify optimal scenarios that minimize disposal costs.
- Model Uncertainty: Recognizes that the disposal cost system cannot precisely calculate all costs. - Analyzing the impact of arbitrary changes in cost allocation ratios is necessary.
- Input Variable Uncertainty: Addresses the uncertainty associated with input variable values or their ranges in the cost assessment system. Sensitivity analysis of input variables helps identify key cost drivers for future reference.

4. Conclusions

In this study, we investigated uncertain cost drivers associated with the disposal system before constructing the cost assessment framework. These uncertain cost factors fall into four main categories: system uncertainty, scenario uncertainty, model uncertainty, and input variable uncertainty. In further study, we can assess the impact of these uncertainties on the overall cost of disposal by conducting sensitivity analyses.

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