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Development of an alternative disposal system for CANDU spent nuclear fuel and a review on the Finnish Posiva's FEPs and scenarios

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1. Introduction

In Korea, around 576,000 bundles of CANDU spent nuclear fuel (SNF) are expected to be generated from the four CANDU reactors at the Wolsong site. So far, the authors have designed a reference disposal concepts with the geological data obtained from the KURT based on the KBS-3 concept [1]. One of the critical disadvantages of the KBS-3 concept is that it requires too large the footprint. Considering the limited area of the Korean peninsula, a new disposal concept should be proposed.

Recently, a new research project has been launched to overcome this weakness. Through a literature survey published in the 2000s, we first selected ten disposal concepts. Then, four candidate concepts were chosen by the expert judgements [2]. Assuming 10 thousand tons of CANDU spent nuclear fuels, we made conceptual designs of four disposal concepts: ① mined deep borehole matrix disposal, ②sub-seabed disposal, ③deep borehole disposal, and ④ multi-level disposal. With the quantitative data such as footprints, safety factors and economic factors from the conceptual designs were produced for the comparison of four alternative concepts. Finally, two-level disposal concept was proposed by applying the AHP together with domestic experts.

The first stage of the long-term safety assessment of the repository is to develop scenarios. In the early work, scenarios were developed by combining the relevant FEPs chosen from the comprehensive FEP database (called 'bottom-up approach'). The bottom-up approach tries to seek all conditions of concern, without focusing on the key issue, which leads to huge amount of effort. More recently, a 'top-down' approach focusing on the safety function of the system components was established by Sweden and Finland to overcome these drawbacks. By combining the bottom-up approach and the top-down approach, a 'hybrid' approaches were proposed [3].

In this paper, we briefly introduced the results of the comparisons among the candidate alternatives and illustrated a conceptual design of the engineered barrier system of the two-level disposal system for CANDU SNF. In addition, we review the Finnish Posiva's FEPs and Scenarios in detail for the long-term safety assessment of the alternative disposal system.

2. Comparison of four candidate alternative disposal concepts

2.1. Mined deep borehole matrix disposal

Long boreholes with a diameter of 1 meter in are drilled for the disposal of CANDU SNF between the construction tunnel at 800 m deep and the operation tunnel at 500 m deep(Fig. 1). Sixty Copper canisters containing 48 CANDU SNF bundles surrounded with compacted Ca-bentonite buffer will be disposed of in a long borehole as shown in Fig. 1, which would remarkably increase the disposal density. The copper canister with a thickness of 10 mm is designed to be fabricated using a cold spray technique [4]. The spacing between the boreholes was determined to be 20 m considering the decay heat.

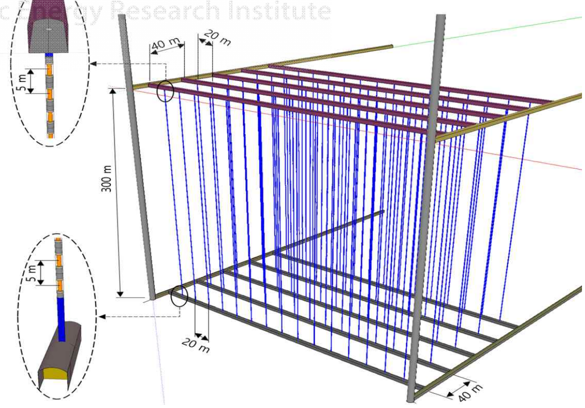

Fig. 1. Conceptual schematic of deep borehole matrix.

2.2. Sea-bed disposal

Currently, CANDU SNFs are stored in a basket containing sixty bundles. The engineered barrier system of the reference disposal system is adopted as is except for location. Considering a situation of difficulty in finding a disposal site on land, we considered a reference disposal system in a host rock under the sea (see Fig. 2). The encapsulation plant and the entrance of the access tunnel are located on land, and they will be dismantled after the closure of the repository.

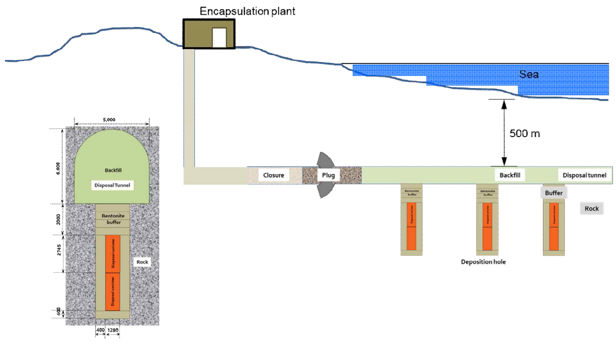

Fig.2. Schematic of a sea-bed disposal.

2.3. Deep borehole disposal

The very deep borehole disposal (DBD) with a length of around 5 km was applied to the disposal of CANDU SNF. A disposal canister was designed with a silicon carbide (SiC), which can contain 63 CANDU SNF bundles. The disposal canisters will be disposed of from 3 km to 5 km below the ground.

2.4. Multi-level disposal

In order to enhance the disposal efficiency, three kinds of two-level disposal system were compared for the CANDU SNF. Among them, the system where all the CANDU SNFs are disposed of at the bottom level was chosen (Fig. 3). The engineered barrier system of the two-level repository is identical to that of the reference disposal system.

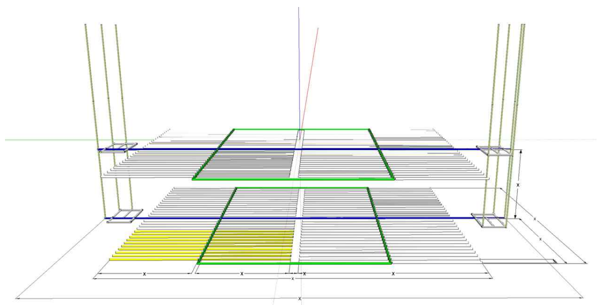

Fig. 3. Concept of two-level disposal for CANDU SNF.

2.5. Comparisons

Five evaluation criteria were established for the comparison of alternatives as follows:

- Public acceptance: footprint, retrievability, non-proliferation
- Safety factors: corrosion lifetime of a disposal canister, migration time of I-129
- Cost: economical factor derived from the disposal cost
- Environmental friendliness: copper and bentonite mass
- Technology readiness level: foreign countries' experiences

A set of quantitative data based on each conceptual design was derived for the evaluation criteria. The AHP together with domestic experts was applied to the selection of the alternative. The multi-level disposal was proposed as the most appropriate alternative.

3. Finnish Posiva FEPs and Scenarios

According to the NSSC (Nuclear Safety and Security Commission) Notice 2021-21, total risk assessment should be based on the radiological exposure scenarios. Generally, the scenarios are the results of combinations of the initial state of the system, the FEPs and the evolution of the system (Fig. 4).

We reviewed the Finnish Posiva FEPs related to the engineered barrier system (EBS) since the EBS of the alternative disposal system is very similar to it. Posiva categorized the FEPs as evolution-related FEPs or migration-related FEPs as shown in Table I. Total sixty four FEPs are considered to be potentially significant for the long-term safety of the engineered barriers [5].

In Finnish regulatory guidelines, YVL D.5, three types of scenarios are defined: base scenario, variant scenarios, and disturbance scenarios. To meet these guidelines, Posiva developed the several kinds of scenarios following a top-down approach. That is, after identifying safety functions of each repository component and the FEPs that could adversely affect the safety functions, the effects of the expected evolution of the repository system are evaluated through the performance assessment (PA). Among the lines of evolutions that lead to canister breaching, radionuclide release scenarios are derived. For each of the scenarios, a set of calculation cases is defined to analyze the potential radiological impacts (see Table II).

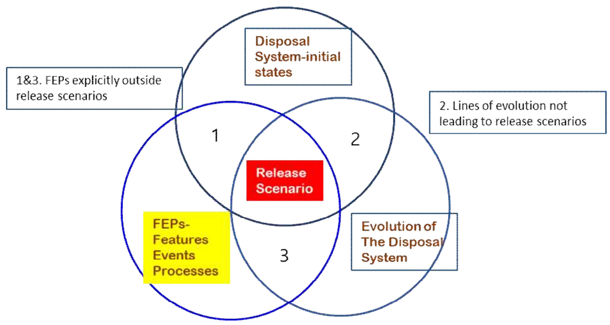

Fig. 4. Relationship between release scenarios and FEPs.

Table I. Posiva FEPs list related to EBS only

	Spent fuel	Canister	Buffer	Backfill	Auxiliary Components
Evolution	Radioactive decay (and ingrowth)				
	Heat generation	Radiation attenuation			
	Heat transfer	Heat transfer	Heat transfer	Heat transfer	
	Structural alteration of fuel pellet	Deformation	Water uptake and swelling	Water uptake and swelling	
	Radiolysis of residual water	Thermal expansion of the canister	Piping and erosion	Piping and erosion	
	Radiolysis of canister water	Corrosion of copper overpack	Chemical erosion	Chemical erosion	
	Corrosion of cladding tubes	Corrosion of cast iron insert	Radiolysis of porewater		
	Alteration & dissolution of the fuel matrix	Stress corrosion cracking	Montmorillonite transformation	Montmorillonite transformation	Chemical degradation
	Release of IRF		Alteration of accessory minerals	Alteration of accessory minerals	Physical degradation
	Production of He gas		Microbial activity	Microbial activity	
	Criticality		Freezing and thawing	Freezing and thawing	Freezing and thawing
Migration	Aqueous solubility and speciation	Aqueous solubility and speciation	Aqueous solubility and speciation	Aqueous solubility and speciation	Transport through auxiliary components
	Precipitation and co-precipitation	Precipitation and co-precipitation	Precipitation and co-precipitation	Precipitation and co-precipitation	
	Sorption	Sorption	Sorption	Sorption	
	Diffusion	Diffusion	Diffusion	Diffusion	
		Advection	Advection	Advection	
		Colloid transport	Colloid transport	Colloid transport	
		Gas transport	Gas transport	Gas transport	
	15FEPs	14FEPs	16FEPs	15FEPs	4FEPs

Posiva claimed that the repository system scenarios are comprehensive because they checked all the identified FEPs influencing the long-term safety are taken into account.

Table II. Calculation cases for base scenario

Scenario	Calculation cases	Description
Base scenario	BS-RC	Reference Case (RC) - one canister with an initial penetrating defect of 1 mm diameter Cautious position selected from a DFN realization taking into account the whole repository
	BS-LOC1	As RC; except alternative position 1 – investigate uncertainties in the selection of flow-related parameters (uncertainty in DFN realization)
	BS-LOC2	As RC; except alternative position 2 – investigate uncertainties in the selection of flow-related parameters (uncertainty in DFN realization)
	BS-ANNFF	Same as RC; Ag, Mo, Nb treated as anions in the near and far field (i.e. geosphere) - investigates uncertainties in the speciation of those elements
	BS-TIME	As RC; uncertainties in the time needed to establish a transport path from the defective canister (1000 years in RC and 5000 years in BS-TIME).

4. Conclusions

A multi-level disposal method was selected among four candidate disposal concepts and proposed as an alternative method for the CANDU spent nuclear fuel from a high disposal efficiency perspective. In order to prepare the radiological exposure scenarios for the alternative disposal method, we reviewed the Finnish Posiva's FEPs and Scenarios used for the development of Safety Case for the construction license. Through additional literature survey, we plan to derive FEPs and Scenarios suitable for the domestic disposal environments.

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