Review Paper https://doi.org/10.7733/jnfcwt.2023.001

A Current Status of Natural Analogues Programs in Nations Considering High-Level Radioactive Waste Disposal

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(Received August 1, 2022 / Revised September 13, 2022 / Approved October 14, 2022)

Several countries have been operating radioactive waste disposal (RWD) programs to construct their own repositories and have used natural analogues (NA) studies directly or indirectly to ensure the reliability of the long-term safety of deep geological disposal (DGD) systems. A DGD system in Korea has been under development, and for this purpose a generic NA study is necessary. The Korea Atomic Energy Research Institute has just launched the first national NA R&D program in Korea to identify the role of NA studies and to support the safety case in the RWD program. In this article, we review some cases of NA studies carried out in advanced countries considering crystalline rocks as candidate host rocks for high-level radioactive waste disposal. We examine the differences among these case studies and their roles in reflecting each country's disposal repository design. The legal basis and roadmap for NA studies in each country are also described. However because the results of this analysis depend upon different environmental conditions, they can be only used as important data for establishing various research strategies to strengthen the NA study environment for domestic disposal system research in Korea.

Keywords: Deep geological disposal, Disposal system, Natural analogue study, Radioactive waste disposal program, Natural analogue program

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1. Introduction

In Korea, Korea Atomic Energy Research Institute (KAERI) has proposed concepts of a deep geological disposal (DGD) system for spent nuclear fuel (SNF) generated from pressurized water reactor (PWR) and Canadian deuterium uranium reactor-pressurized heavy water reactor (CANDU-PHWR). In addition, as the government also has tried to reduce and recycle radioactive waste, KAERI has also developed a DGD system for the disposal of radioactive wastes from pyroprocessing of PWR SNF. In this DGD system, a high-level metal waste generated from pyroprocessing of PWR SNF is buried in crystalline rock such as granite. A design and performance assessment (PA) for the system is carried out using mainly geological data acquired from KAERI underground research tunnel (KURT). Two disposal systems are being considered according to the direction of disposal holes (vertical or horizontal). Disposal containers for radioactive waste are copper-iron type and expected to have a life expectancy of 1,000 years. The copper layer on the surface of the container is approximately 1 cm thick and manufactured using the cold display technique [1]. For a buffer material, a domestic Ca-Bentonite with a dry density of 1.6 $g{\cdot}m^{-3}$ is being proposed. KAERI has also been developing design and safety cases for DGD system of not only SNF with pyroprocessing but also domestic SNF.

Proving the long-term safety of DGD of radioactive waste is very challenging, moreover the most representative issue in DGD is assuring the safety of radioactive waste disposal systems over several hundred thousand years. To this end, a safety case has been developed as an integrated concept that combines evidence, analysis, and discussion to assure and reliably predict the safety for a long period of time after the closure of the disposal site. However, the licensing process for a high-level radioactive waste (HLW) disposal facility takes a long time, and has problems that require vast multidisciplinary approach, and considerable economic costs. Moreover, nobody can guarantee the safety of disposal repository in hundred thousand years. Especially many advanced countries with disposal programs for high-level radioactive wastes have been trying other challenges to improve the reliability of the safety assessment and public acceptance of their own DGD system, one of which is NA study that can be the intuitive way to give reliability of the long-term safety and PA of DGD system. Safety cases of DGD system have been researched recently with increased comprehensiveness using the broader concept of safety case including NA study while maintaining trust based on quantitative evaluation.

Regardless of the NA studies conducted worldwide in the past few decades, their scientific application has been gradually acknowledged only recently. NA study provides important elements or conceptual models in designing DGD system in many cases, being able to elicit quantitative or qualitative information about the migration of nuclides in multi-barrier system components and providing easily acceptable generic information of DGD to the public [2]. In addition, NA studies on geological and palaeological systems are extremely useful in proving the long-term stability and safety of DGD sites. In other word, NA study based on the analogues remaining in the nature can provide evidences required for safety assessment (SA) to build up confidence regarding the long-term performance of a DGD system, furthermore the NA studies can play an important role in building a relationship with and educating the public with reference to radioactive waste disposal. Thus several countries have conducted some international joint studies for NA and disposal programs suitable for their own environmental conditions in world-wide natural analogue sites. These NA data are evaluated based on the proper study sites and through analysis of the NA corresponding to the component of the DGD system, supporting alteration mechanism over a long period.

Thus, this study aims to develop the domestic NA study technology by establishing the basic concepts of NA study, and review and analyze them through overseas NA study cases in Finland, Canada, the United States, and Spain.

Table 1. Milestones of SNF disposal program in Finland modified [3]

Year	Major past and future history
1987	• Preliminary site surveys and characterization at five sites
1992–1997	• Detailed site surveys and the characterization at four sites (Olkiluoto, Romuvaara, Kivetti and Loviisa)
1999	• Proposal for the construction of disposal facilities at Olkiluoto (Posiva)
2000	• Site selection of Posiva (STUK)
2001	• Approval for construction of URCF ONKALO by the Parliament • Final site selection (Olkiluoto) and various studies on DGD at ONKALO
2004	• Start of Excavation work at ONKALO • Trials for various construction technology including site-specific tunneling
2005–2007	• Development of a post-closure safety case after closing the SNF disposal facility
2012	• Completion of ONKALO • Submittal of the construction license application for a permanent disposal facility
2015	• Granting construction license for disposal facility
2016	• Start of construction of SNF disposal facilities

Moreover, through this study, we intend to present the direction for efficiently producing data on the domestic NA study and to find utilization plans and perform data accumulation of systematic information.

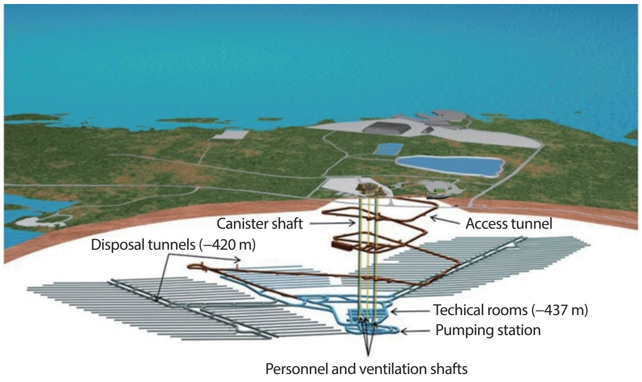


Fig. 1. A schematic presentation of the layout of the ONKALO and the network of disposal tunnels [3].

2. Finland

2.1 Radioactive Waste Disposal (RWD) Programs in Finland

2.1.1 Current Status and Roadmap of Finnish RWD

Finland's disposal program and NA study are expected to be useful for the Korean reference HLW disposal system because crystalline bedrock has been considered as SNF disposal site in both Finland and Korea. Finland currently operates a total of four PWRs Interim storage of SNF and disposal of low- and intermediate-level waste (LILW) have been performed at the Loviisa site, since 1978 and 1998, respectively, and at Olkiluoto nuclear power plant site since 1987 and 1992, respectively [3]. Finland's disposal program of SNF began with a study of geological disposal in 1978 Finland establishing a geologic disposal plan for SNF in 1983 conducted a detailed site survey for geologic disposal from 1993 [4]. In 2001, Olkiluoto was finalized as a geologic disposal site, and various geological, hydrological, and geochemical studies have been conducted on DGD at ONKALO (Fig. 1), an underground rock characterization facility [5]. Milestone of SNF disposal program is presented in Table 1. Posiva eventually applied for permission to operate SNF disposal facilities in 2020. With permission to operate SNF disposal facilities, Finland will begin disposal of spent fuel for the first time in the world from the 2020s.

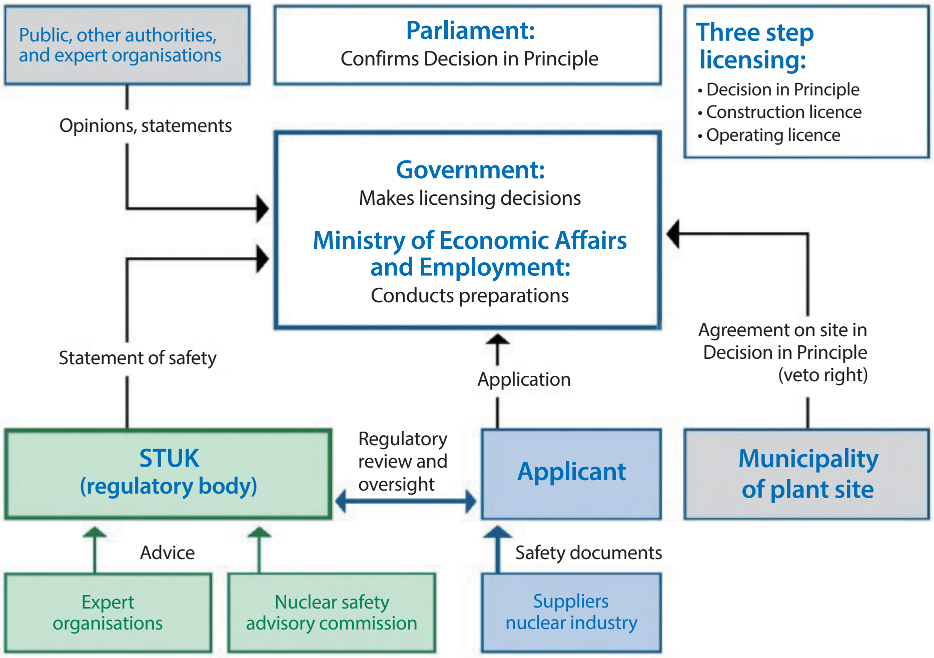


Fig. 2. Administrative flow chart for Finnish radioactive waste disposal facilities [3].

The preparations for operationalizing the disposal site are underway with the goal of starting in 2023.

2.1.2 Legal Basis

Finland enacted a law on nuclear use and radiation protection in 1957 [3]. The current Nuclear Energy Act and the Radiation Act were published in 1987 and 1991, respectively, and have been subjected to various amendments to date. Among them, according to the sections of the Nuclear Energy Act mainly relating to the final disposal of SNF, all wastes should be classified into SNF and LILW; SNF has to be disposed in a deep repository facility. On the other hand, LILW is managed in near-surface landfills or rock caverns for activity less than 100 $kBq \cdot kg^{-1}$, and in intermediate-depth rock caverns for anything exceeding that value [3]. The Nuclear Energy Act describes the principles for ensuring safe use related to nuclear power, such as the safety use of nuclear power and the safety responsibility of power generation operators. It also specifically mentions the roles of the inspection and test laboratories while assessing nuclear safety devices, under the supervision of the regulatory agency, the radiation and nuclear safety authority (STUK) [6]. Legally enforceable regulations such as Nuclear Energy Decree and STUK regulation form the subsystems of the Acts. Based on Finnish regulatory guides (YVL), a subordinate concept of regulation safety, nuclear energy safety is ensured in the following five categories [7]: 1) safety management of nuclear power plant facilities, 2) plant and system design, 3) radiation safety of a nuclear facility and environment, 4) nuclear materials and waste, and 5) structures and equipment of a nuclear facility. The YVL guides are self-revised through setting of more goal-directed and user-oriented requirements. Finland adopted direct disposal of SNF without any reprocessing, as it is regarded as HLW. It is mandatory to apply for a plan to the government from the beginning to construct a disposal facility for the final disposal of SNF, for which the government provides a Decision in Principle (Fig. 2). Finland also has legal procedures to apply for construction and the operation after the Decision in Principle approval. It is

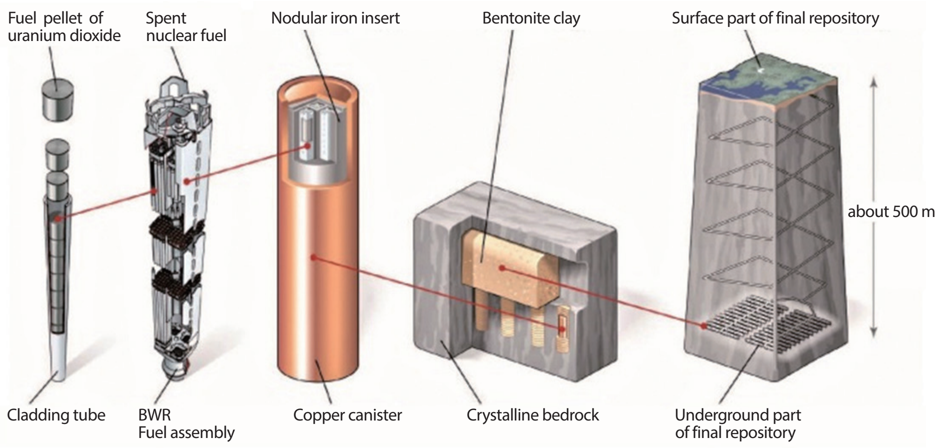


Fig. 3. KBS-3 Multiple barrier system for final disposal of SNF [8].

Table 2. Comparison between disposal system components and NA study in Spain [42]

Components	NA study	
Spent fuel & Vitrified wastes	U-mineral deposits (Uraninite): volcanic glasses	• UO_2 behavior (stability/dissolution) • Role of redox processes in RN migration • Mobility and retardation (retention in 2nd phases-speciation-solubility)
Canister (Steel, Cooper)	Fe and Cu mines Metallic pieces	• Canister corrosion • Redox conditions (fronts) • Mobility and retention in 2nd phases
Argillaceous barrier (Bentonite)	Bentonite and isolating clays	• Longevity of bentonite: Illitization • Cementation and impurities precipitation • Sorption in clays • Hydraulic barrier and colloid filter • Interaction with other Near Field Components • Coupled THC processes: effect on bentonites
Tunnels and seals (Concrete)	Hyperalkaline media: archaeol. cements	• Hyperalkaline waters interactions • Mobility and retention in 2nd phases (speciation-solubility in high pH conditions)
Geosphere (Granite, Clays)		• Transport and retention processes in geological media: - Speciation-solubility, coprecipitation - Redox conditions (fronts) - Matrix diffusion, sorption, ion-exchange - Microbial activity - Colloids

strictly prohibited to use nuclear power without permission granted by the Nuclear Energy Act. The full responsibility for the disposal of radioactive waste in Finland lies with the producer who generates it, including all expenses incurred for disposing waste during operations and decommissioning the waste generated or remaining after the closure of nuclear power plant facilities. The fund for disposal of SNF is administered by the Nuclear Waste Management Fund.

2.1.3 Main Concepts of Disposal Repository at Olkiluoto

Posiva's permanent disposal of SNF uses the KBS-3 concept, the final disposal system developed for SNF by SKB, a Swedish nuclear fuel and waste management company. The main concept of KBS-3 is a multi-barrier system that includes both engineering barrier system (EBS) and natural barrier system (NBS). A canister in EBS, stored with spent fuel rods, is placed in a disposal hole 400–700 m underground in crystalline or sedimentary rocks, which is first filled with buffer materials, and then the disposal tunnel is blocked with a backfill (Fig. 3) [8]. In Table 2 of Posiva report [9], safety functions are assigned to the barrier component in KBS-3. On the other hand, in NBS, referred to as the geosphere, HLW is isolated from the ecosystem for approximately millions of years by blocking the joints and fracture sections that provide a fast pathway for nuclide movement or groundwater infiltration. The far field (geosphere) plays a role in preventing damage to EBS by stably maintaining the physical and chemical environments in the repository and retarding the release of radioactive materials outside. In DGD systems, the host rock of the disposal site acts as an NBS by providing a natural barrier function with a high level of containment and isolation for SNF. Rock bed plays a role in supporting the isolation function by providing mechanically and chemically stable conditions for disposal containers and buffer materials. DGD has following advantages: 1) the concentration of dissolved materials that adversely affect copper and buffer materials is low, 2) inflow of harmful radionuclides inside the disposal repository is constrained because of extremely slow groundwater speed, 3) dynamically, the disposal tunnel and hole retain their shape for a long period, and 4) radionuclide migration through fracture generation is retarded because of the stress condition of rock. Posiva constructed the ONKALO in Olkiluoto to understand the characteristics of the bedrock [10]. The geology of Olkiluoto site is extremely complex and characterized by crystalline bedrock dominated by foliated gneiss with a few brittle deformations across the DGD areas. Giant coarse particles of granite pegmatite also exist as an embankment in the region. Studies on the direction of the stress field and strength of the bedrock have also been conducted.

As one of the main components of EBS, the canisters are composed of a double-layer structure where 50 mm thick copper wraps an internal structure made of cast iron. In the performance assessment in the Posiva [11], radionuclide releases are not expected at least 100,000 years under expected evolution of conditions. Thus the canisters, protected by buffer, are designed to have a lifetime that much to resist potential events over this period, and tens of thousands of years are often assumed conservatively. The cast iron and external copper layer help in resisting mechanical stress and corrosion, respectively, and canisters have to be resistant to all known corrosion phenomena for a period of at least 100,000 years. They also have to maintain their original form, withstand mechanical pressure equivalent to at least that at 500 m depth, and consider an expectedly heavier load during the ice age as well.

Buffer materials play a major role in retarding groundwater infiltration and movement of radionuclides during the safe disposal of SNF, and should have low hydraulic permeability and conductivity, self-sealing capability, and high durability. In addition, substances with that break easily, such as concrete, or organic substances, such as asphalt, are also excluded as buffer material. Bentonite is a commonly used buffer in the DGD of SNF. It swells in contact with water, which helps fill the pores of the buffer and fractures in the bedrock, improving the safety of DGD. The swelling property of the installed bentonite works as a very important safety function of buffer in the DGD. The first is to retard movement of dissolved species that can cause the canister corrosion and the radionuclide release from a damaged canister. The second is to balance the buffer mass between installed components with different initial densities. The last is to prevent bacteria activity. According to formulation based on canister (SKB 2006) in the Posiva report [12], the hydraulic conductivity criterion, closely related to the swelling pressure, was lower than 10^{-12} $m{\cdot}s^{-1}$ and the diffusion is dominant on this hydraulic gradient zone. Under the premise of the saturated buffer homogeneity, the swelling pressure criterion was judged to be at least 1 MPa with the concept and the boundary conditions. When considered in the bacterial inactivity condition, the swelling pressure criterion of bentonite increases to at least 2 MPa.

During the disposal of canisters containing SNF in the disposal hole and installation of buffer material, an empty space (gap) is formed between the buffer material and bedrock, because certain spaces must be provided for installation of the buffer and backfill material or for the uneven surface of the excavated disposal hole. These empty spaces between disposal tunnels must be filled with backfill to ensure the impermeability and heat transfer efficiency of engineering barriers. The backfill material is filled as a block with a mixture of bentonite and crushed rock in the ratio 3:7, and the space between the backfill block and the rock is filled with bentonite pellets. Because high packing density is advantageous for increasing barrier performance, the backfilling material is not used separately as pellets or granules, but in the form of a pellet-granulated mixture [13]. In Finland, 10 mm of empty space is allowed between the disposal container and the buffer material, and 50 mm between the buffer material and the inner wall bedrock of the disposal hole [14].

Furthermore, to isolate the SNF completely from the environment and sustain the natural environmental conditions, no fluid flow or travel path can be allowed between the underground surface and the disposal tunnels and holes. While the disposal site is closed by covering it with a backfill material and a plug, it is appropriate to use low-pH concrete to seal the crushed area containing groundwater for mechanical stability. Clay may also be used as the closure component, which is suitable for effectively sealing the bedrock.

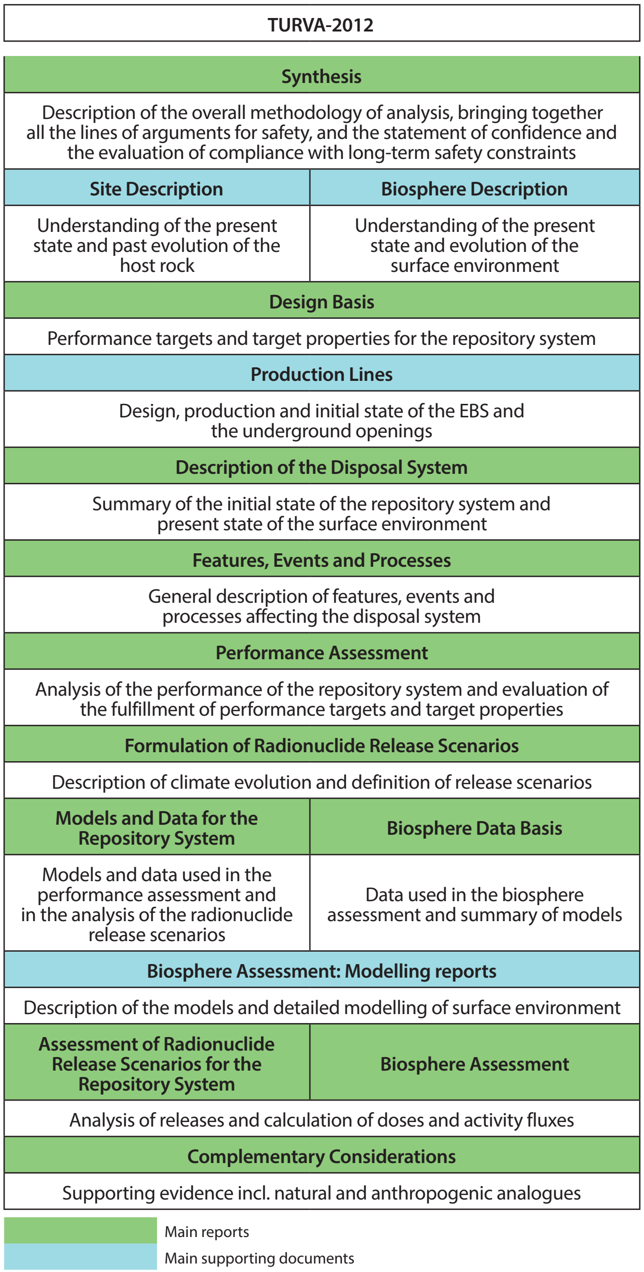
2.2 NA Studies

2.2.1 Legal Basis and Complementary Considerations (CC) Report

In Finland, although the primary responsibility for SNF waste disposal lies with the users generating it, control authorities and political decision makers play a key role in the licensing process at various stages. At the licensing stage, a scientific consensus that the planned process will benefit the entire society must be demonstrated [15]. For scientific consensus, consistent information, data, and calculation results indicating that an appropriate level of safety has been achieved should be presented, which can be demonstrated through a safety case, ensuring reliability of disposal safety. NA studies can be used as supplementary resources for the public to perceive the safety of disposal system by conducting comprehensive studies at natural systems and sites on the behavior of various materials and processes expected to be used in the design of disposal systems. Thus, a good study of appropriate NA systems provides crucial information for improving the understanding of short-term and long-term behavior and the reliability of SA modeling.

The NA study in the Palmotu region of Finland began in 1987 as a national joint study project including geological structures, hydrogeology, oxidation-reduction processes, geochemical modeling, and migration processes modeling, being conducted with the aim of comprehensively understanding and characterizing the uranium and thorium in the crystalline rocks [14]. Palmotu was the only site in Finland for vast geological research in the early 1980s, In 1996, the Palmotu NA study was continued through international efforts funded by Geologian tutkimuskeskus (GTK), STUK, SKB, Empresa Nacional de Residuos Radiactivos Sa (ENRESA), Centro de Investigaciones Energéticas, Medioambientales Tecnológicas (CIEMAT), and Bureau de Recherches Géologiques et Minières (BRGM). During 1999–2003, the IAEA launched a Coordinated Research Project (CRP) for the use of safety indicators (concentrations, flow rates) selected in the assessment of radioactive waste disposal. This research project aimed to achieve international consensus by contributing to the long-term SA of radioactive waste disposal founded on additional safety indicators based on observations from natural systems.

In 1999, Finland chose DGD as its SNF disposal



TURVA-2012

Synthesis

Description of the overall methodology of analysis, bringing together all the lines of arguments for safety, and the statement of confidence and the evaluation of compliance with long-term safety constraints

Site Description	**Biosphere Description**
Understanding of the present state and past evolution of the host rock	Understanding of the present state and evolution of the surface environment

Design Basis

Performance targets and target properties for the repository system

Production Lines

Design, production and initial state of the EBS and the underground openings

Description of the Disposal System

Summary of the initial state of the repository system and present state of the surface environment

Features, Events and Processes

General description of features, events and processes affecting the disposal system

Performance Assessment

Analysis of the performance of the repository system and evaluation of the fulfillment of performance targets and target properties

Formulation of Radionuclide Release Scenarios

Description of climate evolution and definition of release scenarios

Models and Data for the Repository System	**Biosphere Data Basis**
Models and data used in the performance assessment and in the analysis of the radionuclide release scenarios	Data used in the biosphere assessment and summary of models

Biosphere Assessment: Modelling reports

Description of the models and detailed modelling of surface environment

Assessment of Radionuclide Release Scenarios for the Repository System	**Biosphere Assessment**

Analysis of releases and calculation of doses and activity fluxes

Complementary Considerations

Supporting evidence incl. natural and anthropogenic analogues

🟩 Main reports
🟦 Main supporting documents

Fig. 4. TURVA-2012 Safety case portfolio [9].

system. Olkiluoto in the southwest of Finland was selected from among various sites including Romuvaara, Kivetti, Hststholmen, and Olkiluoto, as the disposal site in 2000. In 2005, it first announced a plan to publish a report on the safety case, and Posiva amended it in 2008 to implement SNF disposal. Based on ISO 9001:2000, the new plan enhanced the safety of disposal with special characteristics derived from STUK's YVL guides. Since the announcement of the revised plan in 2008, this disposal portfolio has been extended to include updates in YVL guides' and feedback received from authorities, and a complementary considerations (CC) report to support long-term safety was included as part of the safety case [9]. This CC report describes various evidences to explain the safety of storage disposal over thousands of years in the Olkiluoto region. In addition, NA research on naturally or anthropogenically generated studies for components and processes related to SNF disposal was conducted to gather evidence on the effects on disposal safety and enhance confidence in safety [16]. The safety case portfolio published in 2012 is presented in Fig. 4.

The management of nuclear waste in Finland is regulated by the Nuclear Energy Act and the Nuclear Energy Decree. According to the Finnish government decree GD 736/2008, the suitability of disposal methods and sites, as well as long-term radiation protection requirements, must be demonstrated by a safety case, which means it should include both the expected evolutionary scenarios and the potential to compromise long-term safety. This safety case states that it contains computational analysis and CC report based on experimental studies involving significant uncertainty or difficulty of quantitative analysis.

2.2.2 Various Fields of NA Study in Finland

A characteristic of Finnish NA study is that the NA study was conducted in the disposal site area with the aim to use it directly in the SA or PA of the disposal system. A representative NA study on rock stability and suitability for disposal site was performed in Olkiluoto. The presence of long-term safe disposal properties at the Olkiluoto site is an important factor in determining the safety of disposal. To ensure of the site suitability for disposal system, it is necessary to understand the overall site and predict its future behavior. In addition, the impacts of various long-term processes such as water penetration into underground rocks, external events such as earthquakes, and erosion on the safety of underground facilities should be discussed. Olkiluoto was determined to be suitable as a disposal site through an assessment concept called Block model or Mosaic structure [9]. Crystalline rock in Finland is well characterized by an elevation-related structural shift in the fracture system surrounding the relatively intact bedrock block. This geological structure forms the basis for the stability of the site and provides information for selecting the location of the disposal hole. This Olkiluoto site will be investigated for the ongoing impact of construction and operation during the current research phase at ONKALO.

In Olkiluoto, disposal facilities can be affected by changing climate long after their closure. In Finland, in general, the permafrost or the colder ice climate can change, and the presence of permafrost in Olkiluoto can significantly change not only the surface environment but also the underlying hydrogeological and hydrogeochemical conditions. Furthermore, the presence of thick ice sheets can have a great impact in terms of changes in the terrain. The main issues are the depth at which the permafrost can reach at the disposal site and its consequent impact on SNF. In particular, a surface of the permafrost repeats a thawing and a freezing with a seasonal cycle. It is saturated by small ponds or wetlands in summer, while the saturated waster within the surface layer is frozen and expands in volume in winter. This repetitive and gradual behavior can result in cracks in the concrete by damaging the finishes and joint parts on the surface of the disposal site [17]. NA studies are being conducted on permafrost in Greenland under conditions similar to those in Olkiluoto during the last glacial cycle. The Greenland NA study project reported that the front-line permafrost depth at the Russell Glacier reached down to 300 m. This project indicates that water generated by melting glaciers can penetrate into the disposal site through fractures, and suggests that oxidation conditions inside the disposal site can be formed through water penetration. However, these assumptions are based on extremely conservative assumptions. Based on current information on the Olkiluoto site, oxidized groundwater has neither reached disposal depth in the past, nor will do in the future.

On the other hand, NA study on the possibility of glacial water infiltration into has been conducted in Palmotu [18]. Palmotu was located on the edge of an ice sheet that was susceptible to the direct impact of glacial water during the last ice age. However, although the bed rock may be susceptible to the penetration of diluted water, its depth was limited to approximately 100 m. Based on these results, it is expected that if Olkiluoto is located on the edge of the ice in the future, the change will not be significantly different from that observed in Palmotu. Furthermore, no significant evidence of oxidative or glacial water residues has been found at the disposal depth of the Olkiluoto site, suggesting a significantly less possibility of glacial water infiltrating the bedrock.

The NA studies for hydrogeology studies, including geological surveys, groundwater measurement leaking into the tunnel, groundwater characteristics, and composition studies, were conducted at ONKALO in Olkiluoto. Geological models were created from geological surveys that provided information such as reinforcement (grouting). The geology of Finland is granite bedrock with low permeability, with fluid movement mainly along fractures. Therefore, through a hydrogeological study at ONKALO, the effect of groundwater moving along the fractures in the granite bedrock on the long-term safety of SNF permanent disposal sites to be constructed can be identified. A hydrogeological discrete fracture network model was constructed with the information obtained for the entire Olkiluoto region [19]. The constructed hydrogeological discrete fracture network model simulated the inflow of groundwater into disposal tunnels and bore holes, and the model was continuously reinforced to accurately simulate the movement of groundwater and nuclides, successfully reflecting the hydraulic and solute migration characteristics acquired from ONKALO. Although the study succeeded in developing a hydrogeological discrete fracture network model down to the depth of the disposal site and simulating the hydrogeological behavior, it exhibited limitations in determining in detail the fracture point origins of the fluid flow. A study on the hydrogeological modeling of fluid flow at the ONKALO site has also been conducted [20]. The bedrock around ONKALO is saturated with groundwater that contains dissolved gases owing to high hydrostatic pressure; however, owing to tunnel excavation, the pressure around the tunnel is simultaneously lowered to a level similar to the atmospheric pressure, which leads to the resolution of the gases dissolved in the groundwater, creating two-phase flow conditions near the underground cavity. The simulation revealed that although methane gas dissolved at a depth of 500 m did not significantly affect the hydraulic properties of the fracture for a few minutes after excavation, long-term research is required to validate it [20].

Furthermore, rock-mechanics research was conducted to characterize the rocks at the disposal site, such as the direction of the stress field and the strength of the rocks. The results of the bedrock assessment can be used to determine the direction and intensity of stress acting in the region of interest and build an economical and safe disposal site. The geological and epidemiological conditions of the rock can impact the occurrence of the excavation damage zone (EDZ), affecting the long-term safety of the disposal site. Thus, determining the EDZ is an important task in rock epidemiological research. The EDZ may be characterized using a ground penetrating radar (GPR) [21]. Posiva conducted field experiments to determine the intensity of destruction and in situ stress of migmatitic gneiss that constitutes the bedrock of Olkiluoto. In Posiva's Olkiluoto spalling experiment (POSE), the fracture network obtained from hydrogeological studies was used as input data for information on rock strength or in situ stress. POSE was conducted in three stages. No damage was observed on the drilling core at the first stage; in contrast, at the second stage, heat damage was observed on the surface of the drilling core in regions composed of relatively weaker rock type. The heat damage was confined to less than 100 mm depth, and the range and depth of the damage could be predicted using numerical analysis [22]. In the third step of POSE, it was estimated that the maximum main stress would reach approximately 100 MPa when the temperature was lower than 100°C, and accordingly, the crack damage threshold in the Olkiluoto region was calculated to be in the range of 85 ± 17 MPa. By the end of the experiment, it was expected that the induced thermal stress would gradually increase over time, resulting in spalling beyond the limit [23]. Additionally, thermodynamic coupling analysis was performed in this step using the 3D discrete element method and comparing the result with those of simulation helped in calculating the spalling strength of the rock beyond which the applied power can produce thermal stress.

Finland also conducted NA study on disposal metal canister corrosion, with a focus on general corrosion, local corrosion, microbial corrosion, and stress corrosion cracking under exhalation/anaerobic conditions. A review paper [24] on copper corrosion at the Olkiluoto site confirmed that it was greatly affected by the prevalent oxidation-reduction conditions in the surroundings. Natural copper and copper sulfide were found in the open fractures of crystalline rock in the U-Ca mineralization zone formed over 1.7 billion years in Hyrkkölä near the Palmotu NA study site. This allowed the copper corrosion process to be studied under similar conditions to those of the disposal site and provided information on the mineral formation conditions. In addition, corrosion by sulfide ions is important for understanding the corrosion in the disposal canisters after the disposal facility closure. Although no prolonged sulfation conditions were observed at the Hyrkkölä site, a few examples were found in the region, which indicates that corrosion had occurred under oxidation and reduction conditions in the past. However, it was observed that most of the copper remained in its natural state, which means that its corrosion proceeds at an extremely slow rate. Currently, regardless of being in contacting with groundwater containing 0.4–4 $mg \cdot L^{-1}$ of dissolved oxygen, the copper in this region still retains the oxidation state. This oxidation state is estimated to have started at least 10,000 to 100,000 years ago, and extremely slow copper corrosion is observed even under oxidation conditions. Notwithstanding the oxidation condition, the slow corrosion is considered to be caused by the film mechanism. In copper-iron disposal canisters, there is a possibility of oxidation-reduction potential change owing to iron intercalation and major changes in this regard may result in generating hydrogen. The maximum corrosion depth was estimated by National Co-operative for the Disposal of Radioactive Wastes (NAGRA) at 10 mm not only in an oxygen-free underground disposal environment but also in an aerobic environment that promotes corrosion. Natural iron weathering has been discovered in basalt rocks on Disko Island in Greenland although no NA studies in Finland have been conducted on iron corrosion. Currently, the depth of iron corrosion is progressing at $0.09–10^{-3}$ mm per 1,000 years, which means iron corrodes extremely slowly.

Finally, the role of microorganisms in the disposal environment was studied using groundwater collected at various depths (32–36.8 m, 119–127 m, and 304–309 m) in Palmotu's R387 drilling hole. The depth sections were classified according to the packer system and a few samples were collected by pulling up groundwater into the surface with a pump. Nitrogen gas injection was used to obtain groundwater sample under anaerobic conditions. The microorganism present here were populated at the rate of $10^4–10^5$ cell·L^{-1}, with iron-reducing bacteria (IRB) and sulfate-reducing bacteria (SRB) being the dominant species in Palmotu groundwater [25]. By depth, both iron-reducing and sulfate-reducing microorganisms were detected in equal concentrations both at the shallowest (32.0–36.8 m) and deepest (304–309 m) depths. The number of microorganism decreased with depth. Although microbial studies in the Palmotu region revealed a reducing oxidation-reduction potential with increasing number of reducing microorganisms, it was not possible to clearly prove whether the oxidation-reduction potential was lowered by microorganism activity. However, considering the microbial species and geochemical properties, it was estimated that the geochemical conditions of the groundwater could be maintained in a reduced state by reducing the microorganisms, which probably allows the reduction of U(VI) to U(IV). The biogeochemical characteristics in these disposal environments will play a role in promoting the safety of the SNF disposal system.

3. Canada

3.1 RWD Programs in Canada

3.1.1 Nuclear Waste Management Organization and Disposal Programs

Canada has decided to adopt a deep geological repository (DGR) approach as the main strategy. DGR means retarding the release of radioactive nuclides over a long period of time using multiple barrier systems. A DGR system comprises an EBS (used nuclear fuel, metal canisters, buffer clay layers, etc.) in near field and a geosphere system in the far field. Barriers both in the near- and the far- fields aim to isolate the radioactive nuclides from the surface ecosystem for longer than 1 million years.

Nuclear Waste Management Organization (NWMO) was established in Canada for long-term management of SNF and adopted a design to accommodate SNF equivalent to 48 Canada deuterium uranium (CANDU). NWMO has been implementing adaptive phased management (APM) approach, which entails the concentrated disposal and isolation of SNF inside suitable geological sites such as crystalline or sedimentary rocks. The APM approach comprises total six phases [26]: 1) site selection and approval of related regulations, 2) site preparation and construction, 3) operation, 4) henceforward monitoring, 5) closure of nuclear reactors, and 6) monitoring after closure. NWMO began the site selection process in May, 2010 [27]. Site selection and regulatory approval will proceed further over the next few years. Subsequently, the disposal site will be constructed for approximately 10 years. The transport of spent fuel and storage arrangements will last approximately 40 years or longer, and the specific period will vary depending on the management of the storage inventory. The repository will then continue to be managed and supervised until the reactor closure and pre-monitoring time.

3.1.2 Legal Basis and Canadian Nuclear Safety Commission (CNSC)

The Canadian government appointed NWMO in charge of long-term management of spent fuel based on the Nuclear Fuel Waste Act (2002). DGR disposal of SNF under federal jurisdiction is subject to the Nuclear Safety and Control Act (NSCA) and related regulations. In accordance with Section 26 of the NSCA, all of activities related to nuclear facilities shall be performed after a certificate is issued by the CNSC. The DGR disposal implemented by NWMO will be conducted within the CNSC's comprehensive licensing system, including the overall system of the repository, including site preparation and completion, operation, and reactor shutdown and termination. The design of Canadian DGR disposal sites has to comply with the following laws and regulations: 1) Nuclear Safety and Control Act, Canada Gazette Part III, Vol 139, 1997 and associated regulations, 2) CNSC Radiation Protection Regulations, 3) Ontario Regulation 854, Mines and Mining Plants, 4) National Fire Code (2010), and 5) National Building Code of Canada (2010).

3.1.3 Main Design of Disposal System

The DGR disposal system comprises underground tunnels and rooms for storing SNF. The key to the design is the storage and isolation of SNF over a long period of time. Although the repository will be constructed approximately 500 m below the surface, but the exact location may vary depending on the geological characteristics of the region. The first step into preparing the repository is ground excavation and the method will vary depending on the characteristics of the site and the final design of the repository. The repository concept requires a deep space of approximately 2 km × 3 km. The actual required space and size can vary depending on several factors such as the characteristics of the bedrock and the appearance depth of the medium required for the repository hole. The storage will include offices, maintenance facilities, service centers, and monitoring and testing spaces. Canada also adopts a multi-barrier system as Canadian storage design, which will prevent nuclear species from leaking into the surrounding environment. A multi-barrier system is composed of the high-density ceramic fuel pellets, the fuel elements and bundles, fuel containers, bentonite clay buffer, backfill, and geosphere [28]. The nuclear fuel bundle was optimized in 2014 to suit the Canadian DGR disposal method. Each nuclear fuel storage box houses 48 spent fuel bundles and is placed in a steel basket in a carbon dioxide steel pipe. Steel pipes can withstand an additional 3 km of ice load expected during the upcoming ice age, as well as the weight of the bedrock covering their top. Coating technology for carbon steel pipes and copper has already been developed to a feasible level in Canada. In the geosphere, sedimentary or crystalline rocks in Canada are considered suitable as disposal sites. The bedrock with negligible groundwater flow will be chosen owing to its low permeability; an area where pore water moves approximately 1 m for 1,000 years and takes approximately 100,000 years to reach to the surface is considered. The repository should be capable of isolating SNF safely under any extreme scenario. Crystalline rock is a common geological feature in Canada. The geosphere is elastic, isotropic, homogeneous, and less damaged, and includes joints partly. The bedrock is assumed to exhibit satisfactory hydraulic conductivity of approximately 10–11 $m \cdot s^{-1}$. However, the hydraulic conductivity increases closer to the surface, and tends to decrease in quality. Low-permeability limestone, covered with shale, is selected in sedimentary rocks. Limestone is elastic, isotropic, and homogeneous, and includes joints partially. The repository is located at a depth of 500 m in the bedrock, and the hydraulic conductivity is required to be approximately 10^{-14} $m \cdot s^{-1}$. However, with decreasing depth, the hydraulic conductivity increases, tending to decrease the quality.

3.2 NA Study in Canada

3.2.1 Disposal System and NA Study

In many cases, NA studies related to DGD system provide important factors or models for design or assessment of DGD system. And it is usually carried out through alternative laboratory research or direct measurement in the field, which simulates the physical and chemical mechanisms that may occur around SNF.

NA study in Canada has also been conducted based on the multi-barrier system. When surrounded by multi-barrier system, SNF is considered to be geochemically and physically stable and unchanged over a long period of time and NA studies with SNF are mainly associated with uranium ore in nature. In nature, UO_2 is the most commonly observed form a product of the uranium chain-reactions. Similar to other substances, they can be concentrated or diluted in nature through biological and global circulation for greater than hundreds of millions of years after created. Uranium is frequently concentrated in a coal, its concentration mainly occurs because of a small amount of outflow from granite, which moves along the groundwater, and then precipitates in a reducing environment. Even in the natural world, trace amounts of dissolved uranium are being reduced around the peat zone. In certain uranium mines, the concentrations of ^{235}U are found to be capable of fission, and in others, no ^{235}U is detected because it has experienced natural fission. The study of various types of uranium ore can provide important information regarding the long-term behavior of SNF. Moreover, NA studies are constantly being studied to examine the impact of climate change events such as freezing on DGR disposal, which may occur over a long period of time. Metals, used for constructing the canisters and storage boxes or concrete reinforcement elements in DGR disposal, are mainly used in the form of steel, with copper and titanium also used. NA study on metals is mainly conducted based on ancient artifacts and not naturally occurring metals by checking the preservation status of substances that have existed for millions of years in certain underground environments. However, there is a potential error in such a study, where only the remaining parts of the discovered metal are subject to the study, and the weathering process of the missing parts is difficult to identify. NA studies should further analyze the reactivity and thermodynamic characteristics of metals and reflect them in the spent fuel management system. Bentonite is considered for the buffer material surrounding the canister. In Canada, clay minerals have been observed to surround the uranium ore in the Cigar Lake study area, serving as a barrier to prevent nuclides from leaking across geological time scale. Although nuclides can move through the bentonite void by diffusion, the movement is extremely limited because of their high adsorption by bentonite, which delays this movement rate.

3.2.2 Legal Basis and International NA Study in Canada

The NA study in Canada is part of a series of studies conducted by CNSC since 1978 to assess the long-term safety of DGR disposal of spent fuel. CNSC is conducting a number of international joint studies along with independent researchers. The studies mainly target crystalline and sedimentary rocks, and the long-term preservation and isolation of SNF using multi-barrier system. The program includes joint research by domestic and international researchers and CNSC researchers, along with those from the University of Canada, the German Geological Survey (BGR), the Institute of Radioprotection et Survey (IRSN) in France, and Canada Centre for Mineral and Energy Technology (CANMET). These joint studies provided CNSC researchers with scientific data obtained from laboratories and sites, which were used to develop and verify numerical models. The first study for the possible construction at a Canadian granite DGR disposal site was investigated during 1978–1996. Then long-term safety of engineering barriers had studied between 1996 and 2008 along with ongoing research on granite. From 2009 onward, various studies conducted to date include those on the possibility of DGR disposal in sedimentary rocks, the possibility of progression in DGR disposal according to rock type, preparation for future proposals, and types of nuclear waste and engineering barriers (especially finishes).

CNSC regulates and manages the overall research related to DGR disposal. In Canada, the safety of DGR disposal of radioactive waste is evaluated through the concept of a safety case. DGR disposal safety case is conducted by assessing the geological information, engineering barrier system information, potential corrosion of container, characteristic evaluation of radioactive materials, and development of safety case models. All projects including the environmental impact assessment are subject to safety case to prepare for possible events following the implementation of the project. Among them, safety assessment related to DGR disposal uniquely contains the concept of a geological time scale. For a long-term safety case, the generally considered series of evolutionary scenarios include: (1) contaminant spills, (2) contaminant behavior, (3) receptor spills, (4) potential hazards from leaks. Safety case for HLW DGR disposal is based on experimental and geological research. Geological research quantitatively evaluates various processes such as groundwater flow rates, which can affect disposal systems. These studies include aspects of geophysical, geochemical, and hydrological geology in certain cases. Geological information is important because it can tell stories over millions of years, linking qualitative and quantitative SAs. However, it is difficult to implement long-term geological information in laboratory conditions and the result may include large error owing to the long-term scale. Therefore, for interpretations with a large time scale, it usually rely more on qualitative interpretation than quantitative interpretation. Here, NA study can supplement this information, providing quantitatively interpretable data through numerical models and lay the foundation for conducting a disposal site safety case.

3.2.3 NA Studies in Cigar Lake

The greatest achievement of the Canadian NA study is that it provided a natural basis to support the SA and PA of the design of the disposal system through the similarity between the natural configuration of the uranium ore in Cigar Lake and the design of the artificial DGR system. And Cigar Lake can be considered as a NA scenario that simulates the extreme design surrounded by certain damaged barrier (Fig. 5). In Canada uranium ore is located in the Cigar Lake region in northern Saskatchewan. The ore does not contain sufficient ^{235}U to cause natural fission. Nevertheless, this area has emerged a great NA site for Canada's DGR SNF disposal [30]. Because the Cigar Lake uranium ore is located approximately 430 m below the surface, which is equivalent to DGR disposal depth. The Cigar Lake uranium ore was formed approximately 1.3 billion years ago, the status of the uranium ore found in Cigar Lake is believed to be the same as hundreds of thousands of years after all SNF generated worldwide by the end of 2002 was left in a single repository. In addition, the uranium ore is surrounded by clay, which can be considered as a natural analog of clay buffers in DGR disposal designs. However, similar to the

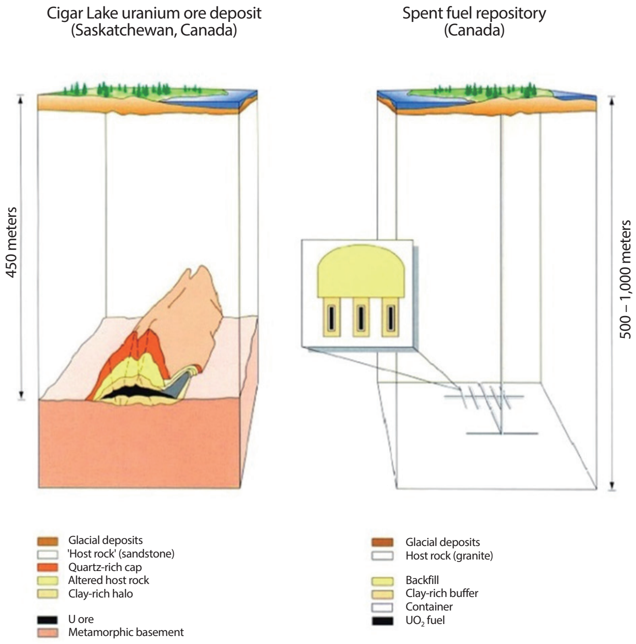


Fig. 5. Conceptual diagram of Cigar lake between conceptual diagram of uranium ore (left) and SNF DGR (right) [29].

actual disposal design, uranium is not contained in a metal storage box and does not exhibit a spontaneous chain reaction. Moreover, there is a severely weathered sandstone layer at the top surface.

The Cigar Lake study beginning in 1982 addressed two things related to HLW repository PA: 1) the safety of uranium ore produced a billion years ago as a natural analog of SNF; and 2) assessment of chemical and hydraulic resistance to nuclide migration as a natural analog of bentonite buffers or clay-based rock barriers.

The release of nuclides surrounding the uranium ore was conceptually and numerically derived [31]. Considering the mathematical, lithological, and geochemical characteristics of Cigar Lake, a material behavior model of the steady state in near field was constructed. The unit medium constituting the material behavior model in the near-field comprised uranium ore, a surrounding clay layer, and sandstone layer over it. It was assumed in this model that the various media are uniform porous materials. Porosity and diffusivity, the most important factors in relation to material behavior, were input separately for the rock and uranium ore.

Cigar Lake uranium ore deposit can be called a closed system, with reasonably assumed steady-state material behavior of the uranium ore and the near-field system. The structure of the system was 800 m long, 50 m wide, 10 m high, and approximately 3 m thick and the surrounding area was simply simulated in the form of clay. The surroundings were assumed to be an extended form of infinite sandstone layer. The uranium mineral groundwater was assumed to be stationary but relatively stagnant, with a uniform concentration of dissolved materials therein. To explain the material behavior of various substances around the uranium ore, a model prediction was performed by inputting the concentration gradient of various substances and verified with helium.

In the results, no measurable levels of nuclides were observed in the soil surrounding Cigar Lake, surface water, lake sediments, and groundwater. Moreover, no leakage was observed from the uranium ore into the surface ecosystem over a long period of time. The Cigar Lake NA study provided a huge amount of data related to physical, chemical, and biological mechanisms to help design the DGR system for SNF. According to the Cigar Lake study [30], the uraninite mineral containing UO_2 is chemically stable under reduction conditions for a period of approximately 1 million years. Only trace amount of uranium have dissolved in the groundwater and moved considerable distances. The clay surrounding the uranium ore naturally and efficiently blocked the movement of nuclides and colloids for a long time. The dissolved organic matter in the groundwater did not play a significant role in the leakage of nuclides. Natural hydraulic barriers and geochemical conditions were also effective in preventing the nuclide leakage. In addition, radiolysis results in Cigar Lake revealed nonsignificant oxidation because of radiation decomposition. Furthermore, through comparison analysis of concentration of suspended particles including colloids and organics, in uranium ore deposit and its surroundings (rocks and sedimentary bedrock groundwater) respectively, it was presented that the clay material around uranium ore sufficiently blocked the colloids. With regard to the near-to-far-field mass transport, the deep reductive groundwater, low-permeability clay layers, and redox buffer capacity ensured that the uranium-containing minerals remained stable without considerable movement. A numerical model was established to evaluate the performance with respect to specific material behavior scenarios. The basic assumption was that the nuclides could travel from the uranium ore toward the upper sandstone layer along a chemical concentration gradient. The model considered the combined effect of the inflow sources, behavioral and solubility-related mechanisms, oxidation and dissolution of UO_2, diffusion and advection, and physical geochemical mechanisms. This conclusion supports the use of bentonite buffers and adoption of clay-bedrocks in repository design. As the uranium plume does not exceed the boundary between the clay layer and the deformed sandstone layer by greater than 0.5 m and considering the dissolved oxygen values observed in the uranium ore, the model predicted the oxidation distance of the clay/uranium optical boundary to approximately 1 m. Finally, the solubility modeling of nuclides in the underground water in Cigar Lake has also identified defects in the current thermodynamic database: 1) the thermodynamic equilibrium constant used in the model was not well-defined or did not exist and 2) the groundwater chemical system was assumed to be in equilibrium. To properly simulate the dissolution and release of trace substances, improvement is required through further research.

4. The United States

4.1 RWD Programs in the U.S.

4.1.1 Disposal of SNF and HLW in Yucca Mountain Nuclear Waste Project

As the U.S. has yet to decide its national policy on the disposal of SNF and HLW, no disposal facilities for SNF and HLW have been constructed to data. While the basic policy of HLW disposal in the U.S. stipulates direct disposal, reprocessing is also under consideration as part of replacing the back-end nuclear fuel cycle. The Waste Isolation Pilot Plant (WIPP) facility in Carlsbad, New Mexico, was designated by the DOE in 1979 as a research and development facility for disposal of Transuranic (TRU) wastes, based on the Nuclear Energy Authorization Act of 1980 (P.L. 96-164).

The Congress designated Yucca Mountain in Nevada as the only candidate site for HLW disposal in the U.S. under the Nuclear Waste Policy Act in 1987. The DOE was instructed to conduct a detailed repository site investigation. By law, the Yucca Mountain repository site was meant to store 70,000 metric tons of waste. The disposal program was implemented from 1987 to 2002, after selecting Yucca Mountain disposal site as the final disposal site. However, the Obama administration withdrew its application for a license to construct the Yucca Mountain repository and finally annulled it in 2009. Subsequently, DOE established the 'SNF/HLW Management and Disposal Strategy' in 2013 based on the recommendation of the U.S. Blue Ribbon Commission (BRC) and proceeded with the follow-up work. In 2013, a U.S. Court ordered the DOE to continue its application for a construction license for the repository, and the U.S. Nuclear Regulatory Commission (NRC) prepared a safety case report related to the site in 2015. Later, the Trump administration passed the revision of the Nuclear Waste Policy Act "NWPA2017" and allocated the budget for the Yucca Mountain project in the fiscal year 2019. The United States has concluded that DGD is the best way to dispose HLW and engineering isolation or closure and recoverability are being considered. The Nuclear Waste Policy Act 1982 empowered three central agencies for high-level dispositions: Environmental Protection Agency (EPA), NRC, and DOE. EPA is primarily responsible for establishing applicable criteria to protect the environment from nuclide release, while USNRC establishes technical requirements for the disposal processes and facility license according to certain criteria. The DOE implements the general process of selecting and recommending sites and provides guidelines for repository site investigations and for the construction and operation of DGD system.

The Yucca Mountain project focused on scientific and engineering research at the site, design of wasteforms to be disposed, and long-term PA of the disposal site. Scientific investigations included the study of site characteristics including geological, hydrological, and geochemical conditions and the evaluation of the various evolution processes of the disposal site over a long time. The Yucca Mountain repository site is located approximately 160 km from Las Vegas, near Nye County, Nevada (Fig. 6) [32]. The groundwater level of Yucca Mountain is approximately 500 to 800 m underground and the disposal site is located 200 to 500 m underground, an unsaturated zone between the surface of the mountain and the groundwater level. The Yucca Mountain's disposal system is designed to allow future generations to choose closure or operation for a longer period of

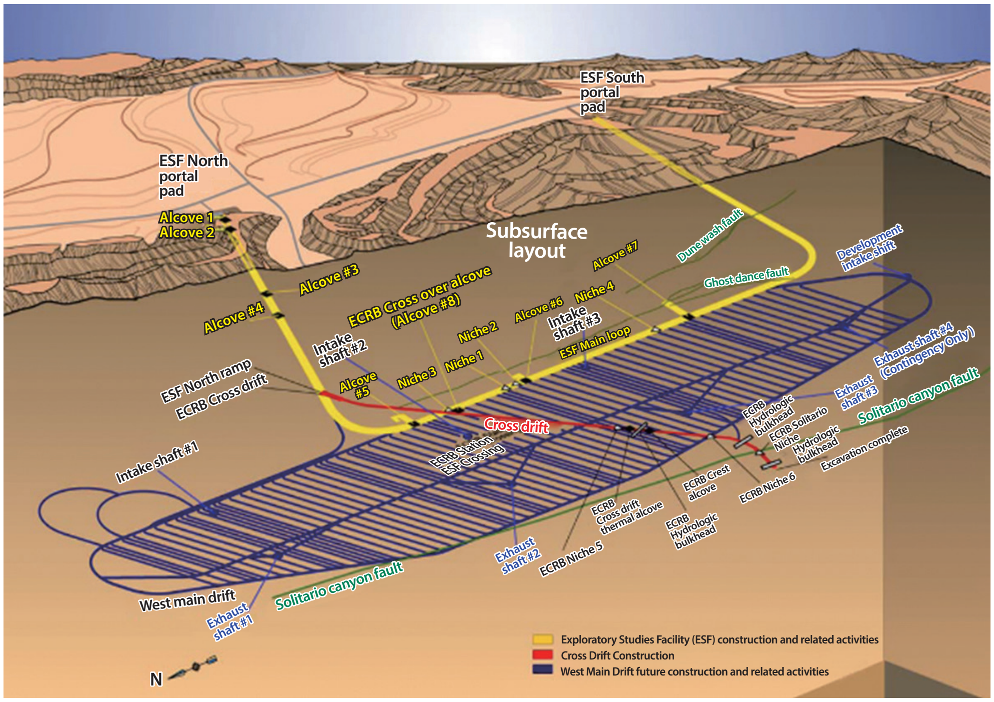


Fig. 6. Layout of Yucca mountain nuclear waste repository site [32].

time. Prior to the decision to close the disposal site, the U.S. is considering ways to make social decisions through monitoring for 300 years. Yucca Mountain was designated as the only survey area for site-characterization by law in 1987. As the country requires underground investigations to receive a construction license for a stratum disposal site, the construction of an Exploratory Studies Facility (ESF) began in 1992 at Yucca Mountain and was completed in 1997. In the ESF, experiments are being conducted to understand the characteristics of the underground bedrock as well as hydrological and geological characteristics.

4.1.2 Legal Basis of Disposal System in the U.S.

In 1980, the NRC established the disposal of HLW in geological repositories, which set technical standards and processes for DGD sites [33] According to NRC, DOE is responsible for the disposal of SNF and HLW and will implement standards for radioactive waste disposal sites. The most controversial regulatory part is the performance criteria for the components of the disposal system. The NRC presented a quantitative criterion for each component; for example, waste packages should be maintained for at least 300 to 1,000 years while the maximum release rate for each nuclide in the annual inventory was set at 1/100,000 or 0.001%. In addition, it was suggested that the groundwater migration time along the fastest path of radionuclide travel from the disturbed zone to the accessible environment should be at least 1,000 years. The standards have been deemed controversial because meeting these proposed standards will cost substantial money and must be supported by a huge amount of research on the geological environment of the site.

The EPA implemented 40 CFR Part 191 in 1985 to provide criteria for the disposal of SNF and high-level TRU radioactive waste. Although this standard does not apply to the WIPP based on the Central Government Act, it is enforced by DOE under the consultation with the state government of New Mexico. In Subpart A of 40 CFR Part

191, "environmental standards for management and storage" provides criteria for temporary storage and long-term Monitored Retrievable Storage (MRS). In Subpart B, "environmental standards for disposal" can be applied to disposal-related environmental leakage, public impact, and groundwater contamination. The criteria presented in Subpart B were determined by assessing the performance of a hypothetical disposal site. The criteria for establishing waste disposal require that nuclide leakage should not reach the geosphere environment for at least 10,000 years after closure.

In 1987, the U.S. Court of Appeal returned Subpart B of 40 CFR Part 191 to the EPA for three reasons. First, EPA did not provide sufficient notice to the public when setting groundwater-related standards. Second, the groundwater protection standard was found to be ineffective, and the court ordered it to be represented because of a conflict with the existing EPA standard, the Safe Drinking Water Act. Third, it was judged that the protection standards for individuals and groundwater for 1,000 years were artificial and the overall standards may have to be inevitably revised.

4.2 NA Study

4.2.1 Policy Background

The EPA requires a PA for 10,000 years [34] for the safety of HLW disposal. The PA entails identifying all the major processes and events and examining their impact on the performance of the disposal system [35]. The NRC requires NA studies to identify processes and events over the time scale required by the EPA and to assess radioactive waste disposal. In other words, the safety case report for licensing should be supported by appropriate field tests, in-situ experiments, and NA studies [36]. The objectives and criteria for the long-term PA of disposal systems are imposed by 10 CFR Part 60, requiring the utilization of NA studies when using predictive models [37]. According to the NRC, the use of methodologies such as NA study will inspire confidence in verifying the models.

4.2.2 NRC and NA Study Program

The primary task of the NRC NA study program is to produce the data required for procuring a license with the DOE. NRC can independently evaluate DOE's work, selectively undertake NA studies and use them for evaluation. The NRC Office of Research is developing a systematic approach to NA study and intends to present proofs or evidences that comply with the NRC regulations. The goal of the NRC HLW study is to reduce uncertainty, and ensure the health and safety of the public by making decisions according to responsible regulations determined by the HLW licensing program. PA is a systematic and quantitative evaluation process that complies with the standards created by EPA and NRC. These assessments comprise concepts related to complex engineering barriers, natural barriers, and computational models, which are subject to technical uncertainty. The overall evaluation system comprises scientific theories simulating systems, laboratory-scale experiments based on both small and short-term processes, verification using laboratory-scale experiment at a large scale and in real time, and long-term studies using NA. Technical uncertainties and errors are calculated and constantly disclosed and supplemented through complex assessments [38].

4.2.3 Conditions and Criteria for Selection of NA Study Sites

The previous decade witnessed a wide range of NA studies conducted by the United Kingdom, Sweden, Switzerland, Canada, Japan, and the United States. Vast international joint research has been supported by the Nuclear Energy Agency (NEA) and the Commission of European Communities (CEC), providing link with the Pocos de Caldas Project, the Cigar Lake Analogue Project, and the Alligator Rivers Analogue Project. A unique point of the US disposal program that U.S. disposal sites, unlike those in other countries, should consider high thermal loads from

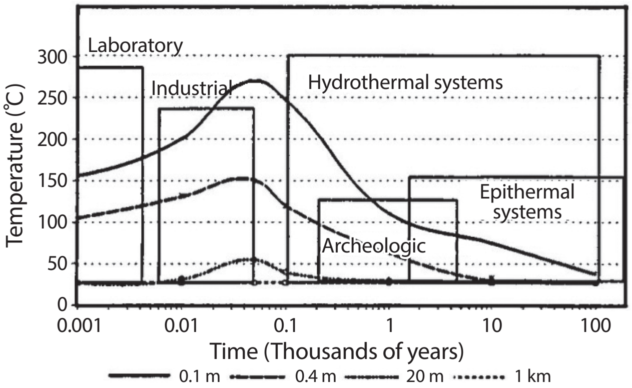


Fig. 7. Application of a NA study to provide understanding for time-temperature ranges for U.S. repository [38].

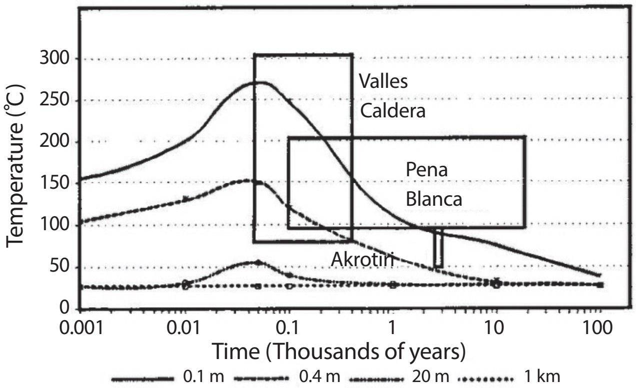


Fig. 8. NA study in the near-field area of disposal site [38].

young fuel, was also reflected in the use of NA study. The design of the U.S. disposal system considers the high temperature of bedrocks, which may cause alteration or degradation owing to possibility of boiling pore water in the unsaturated zone. Internationally, there is little interest in temperatures above 100°C in the disposal system because the disposal site and waste maintain a lower temperature. Currently, a proposed design of the U.S. disposal site is considering temperatures above 100°C during the initial 1,000-year period. Considering the unsaturated and oxidizing conditions, the design of the US disposal system is clearly different from other countries.

The temperature profiles presented in Fig. 7 represent the source of information (NA study site) for various parts of the time-temperature history expected to improve the understanding of the performance of the U.S. disposal system. NA study with the ancient artifacts can extend the time from 100 to 5,000 years. In a nature, it can provide information for 100 to 1,000,000 years. These systems also include hydrothermal systems provided with information about the effects of heat and epithermal systems in low, close-to-surface locations. The system of the NRC NA study plan is being continuously developed according to the time-temperature curves.

The unique feature of the U.S. disposal design is the consideration of higher temperature environment compared with those in other countries. Also, these high temperature curves are typically expected to be similar to those observed around waste disposal containers. The time-temperature curve of NA studies for near field is presented in Fig. 8, and represents the range of NA studies designed for reducing the near-field uncertainty in the current NRC system. The Mexican Valles Caldera and Pena Blanca projects provide information on thermal stability in the bedrocks and the mobility characteristics at the temperature and groundwater saturation levels. The Akrotiri site in Greece provides information on the corrosion and movement characteristics of corrosion products in near-field system area. The Akrotiri site has been buried sufficiently for 3,600 years, the exposure temperature is clear, and its geochemical properties are similar to those at the Yucca Mountain site. However, the hydraulic characteristics of this site differ considerably from that of the Yucca Mountain, causing difficulties. Uranium ores in the Tuff bedrock environment located in Chihuahua, Sierra Pena Blanca, Mexico, were also investigated in conjunction with the alteration and migration of SNF. Uranium migration under unsaturated conditions and the alteration of bedrock in a low temperature environment are major research topics and these processes are also expected to occur in the U.S. disposal system. The NRC' study on the Oklo mine was conducted with the Commissarial Energie Atomique (CEA) and focused on organic properties

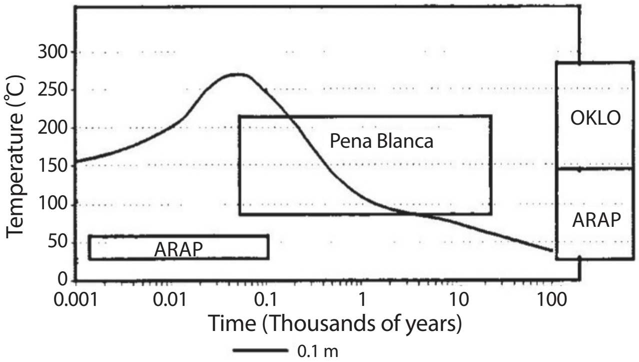


Fig. 9. SNF Natural analogues versus peak repository temperature [38].

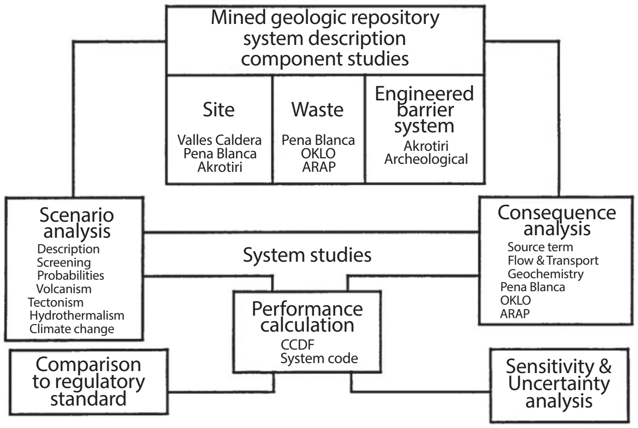


Fig. 10. Conceptual flow chart of PA with contribution of NA study [38].

affecting uraninite alteration and nuclide retardation. Vast research on the mobility of uraninite and fission products has been conducted greater than those in CEA and CEC. The NRC utilize information related to the impact of granite penetration near the Oklo mine surveyed by the CEA and CEC (Fig. 9). The broad interpretation approaches used in the NRC NA study are provided in a flow chart (Fig. 10). Processes at high temperatures and disruptive scenarios are being emphatically considered in the NRC program. Scenario development can be performed using NA study. In addition to the disruptive scenario, if NA study sites are available for simulating abnormal rain and climate change, data can be obtained and used at these sites. Moreover, sensitivity analysis for coupled processes is another productive area that NA studies can perform. NA studies have particularly important meaning for coupled processes, through which it can diversify the parameters. Furthermore, when NA results are compared with a few constant parameters measured in the laboratory, NA studies can provide parameters with greater diversity.

5. Spain

5.1 RWD Programs and Policies in Spain

Spain is the only country in the world to implement a state-owned nuclear industry policy. ENRESA, a state-owned agency, was established in 1984 to design the policy for managing and decommissioning radioactive wastes in the nuclear power plants of the country. In addition, the Consejo De Seguridad Nuclear (CSN), Nuclear Safety Council, establishes the key principles, standards, and regulations for nuclear safety. The agency management system for SNF and radioactive wastes in Spain is presented in Fig. 11 [39].

While the sixth radioactive waste management plan strategically focuses on the commissioning of centralized temporary interim storage (CTS), a DGR is expected to be available for final management by the 2070s [40]. Spain has chosen an open cycle, meaning that the SNF is not reprocessed and is temporarily stored in the nuclear plant's pool or other individual or centralized temporary storage, waiting for final management at the DGR. Only SNFs from the Vandellós I nuclear power plant and small amounts from the José Cabrera and Santa María de Garoña plants have been reprocessed. However, the further reprocessing was cancelled in 1983 and the SNF was stored in the plant. Spain is operating a very low-level waste (VLLW)/intermediate level long-lived waste (ILLW) disposal facility and SNF is expected to be stored in CTS. In mid-2006, Congress approved ENRESA's plan to develop a CTS and safety authorities approved the design of storage facilities similar to those in Habog' in the Netherlands. In December 2011, the

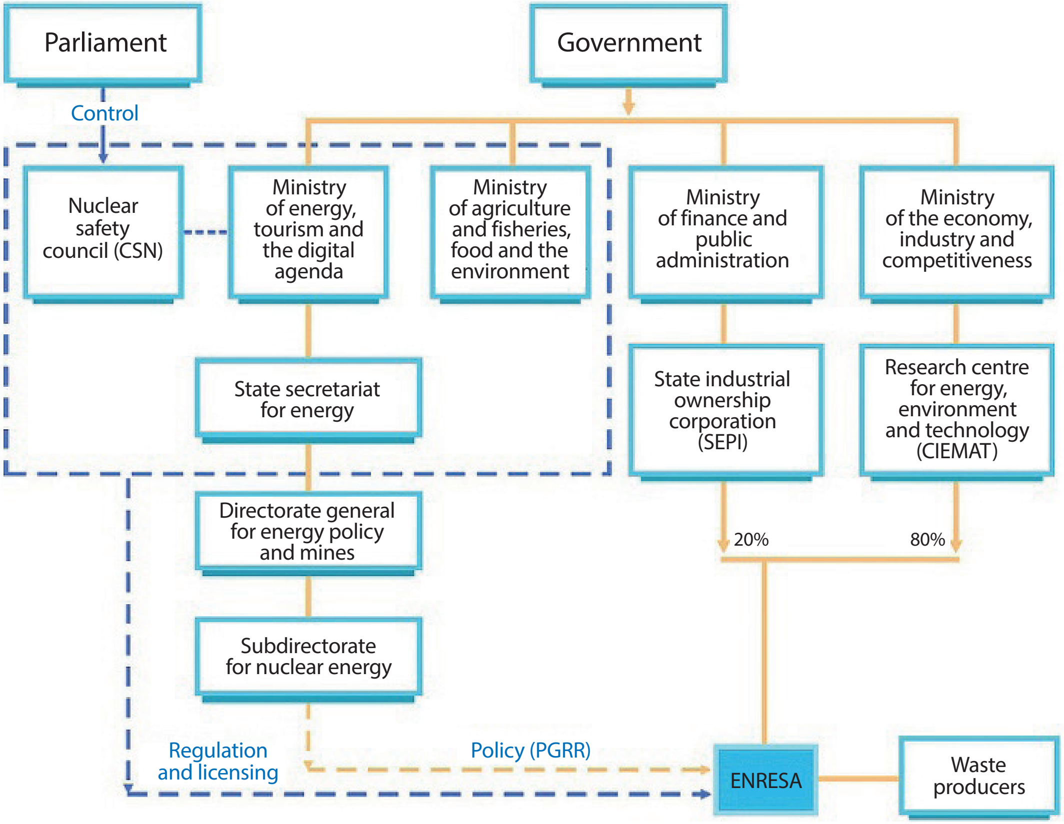


Fig. 11. National agency system for management of SNF and radioactive waste in Spain.

ministry selected a site at Villar de Canas in Cuenca province with a provision of a 60-year storage period. The General Radioactive Waste Plan (GRWP) is revised every four years and the seventh GRWP is currently in progress. For responsible and safe management of SNF and radioactive waste, Spain established a community framework following the Council Directive 2011/70/Euratom of July 19, 2011 and decided that DGR was the safest and most sustainable option for SNF and HLW management.

5.1.1 Main Concept for Disposal System

Spain has decided to directly dispose the SNF and radioactive waste. The DGR method for direct disposal is based on the multi-barrier (a series of artificial and natural barriers) concept [40], which defines two barriers and their components between the waste and the biosphere. The components of the artificial barrier comprise the SNF or waste, storage containers, and fillings barrier. On the other hand, natural barriers are characterized and decided according to functional requirements that enable the efficient functioning of the artificial barriers and entire system. The components of the natural barrier include the geosphere and biosphere. The reference concept envisions the final storage of SNF and other HLWs in carbon steel capsules surrounded by suitable buffers. The capsule is located in a horizontal tunnel located at a sufficient depth, and its design is dependent on clay-based or granite-based bedrocks.

5.1.2 DGR Option Study

Since 1985, ENRESA has studied DGR options in four basic directions [40]: 1) the site search plan is conducted to collect the sufficient information to assure that the subsoil of Spain contains abundant granite and clay layers where disposal facilities can be built, 2) the conceptual design of the disposal facility for each the stated lithological context should be generated based on the common among all of them, 3) SA of conceptual design for disposal facility at granite and clay conditions includes the result of R&D plans and it is complied with the safety and quality standards, and 4) successive R&D plans contribute to participate in global research projects for the accumulation of know-how in the underground laboratory. In Phase 1 (1986–1996), a program on the DGR site investigation was conducted, and a geological strata list was prepared after appropriate analysis. In Phase 2 (1990–2004), DGR design and SA were performed from three perspectives: first, establishing the disposal concept and fundamentals design based on carbon steel canisters horizontally placed parallel to a gallery under the assumption of Ca-bentonite sealing; second, enhancing the fundamentals and principles of the concept; and third, optimization by examining the design of the disposal repository. Spain focused on its considerable domestic R&D for establishment of a DGR storage. As a result, two general designs, adapted from granite- and clay- type, and SAs related to them are now available. These developments will serve as a foundation for the selection of sites and the DGR implementation. The Spanish DGR program was activated along with recommendation of IRRS-ARTEMIS combined with the integrated regulatory review services and integrated review service for radioactive waste, spent fuel management, decommissioning and remediation. The draft of the seventh GRWP currently in process considers the DGR disposal method as the preferred and basic option for SNF and HLW management.

5.2 NA Study in Spain

CSN has led various NA programs domestically and internationally. To promote the reliability of the SA of DGD, a novel approach methodology was required internationally, which was launched in 1997 after national regulations such as NRC 10 CER 63 and an international documents such as IAEA TECDOC 975. Initially Natural and Archaeological Analysis (CSN NAA Study) was domestically established and expanded into a full-blown NA study system through a joint study in 1999. However, difficulties in supply of direct data to PA models have led to the establishment of the supplementary role of NA study in the development and verification of the conceptual model. As part of the fifth EURATOM FP supported by the European Commission (EC), Spain participated in the network to review the NA studies and their applications to repository SA and public communication (EC NAnet) [29] in 2002. ENRESA also announced the results of three major NA projects (MATRIX, ARCHEO, and BARRA).

ENRESA conducted a CSN NAA study, launched in 1999 by CSN's HLW department, in collaboration with the CIEMAT and the other domestic universities, which had focused on application of natural and archaeological analogues for HLW DGD PA and the public communication for three years. Achievement of the CSN NAA project was a vast collection of NAA studies and 19 major SA studies, including various detailed and technical contents being provided to the public. The NAA project had progressed with the selection of target natural analogues, identification of processes and DGD components susceptible to NA information, systematic analysis of 43 natural analogues and eight archaeological analogues, detailed contribution analysis of NA to the SA of the DGD system, and analysis of supplementary information for communication purpose. As a result, multiple documents were published, including NAA catalogs (CSD 1+D document) [41], greater than 2,000 references on NAA and SA, and illustrative synthesis of the study for unprofessional audience. NA studies were reconstructed in Table 2 [42] in relation to the components of the disposal system, which was based on the illustrative synthesis of the study according to CSN 1+D. Moreover, the contribution of NA study to SA model of DGD system was evaluated as well, and the NA study cases present therein have been used in the development and verification of PA conceptual models for DGD system comparing between the Yucca Mountain NA study [43] and research of Altamira and Karchner caves in Spain. However, the NA study results were only used as indirect and supplementary methods to identify the practical use in the 19 SA models and could not be input directly into DGD PA models. This is because most of DGD programs had little NA information available in their early stages, and the precision of the NA study itself was too insufficient to be applied to the initial and boundary conditions of the DGD PA model. However, NA study also played a key role to improve the reliability of the DGD system as a means of communication with the public. Vast amounts of NA study-based information were rearranged and converted into brochures, videos, publications, internet resources (web pages), and other activities for communication purposes.

On the other hand, the NAnet project examined of the use and understanding of NA recommendations for future practical applications, which focused on the effective methodology of NA study for supporting the reliability of PA and SA models and construction of the systematic foundation for NA study [29]. One of the meaningful results of the project is an extensive collection of reviews of greater than 70 individual NA studies, dealing with transportation of radioactive nuclides around uranium ore (e.g., Alligator Rivers, Oklo, Cigar Lake, and Pȩos de Caldas) and mechanical NA study such as bentonite clay stability. Moreover, NAnet project expanded the scope of the retardation and transport studies for radioactive nuclides into the geosphere-biosphere domain, which involves wide investigations that can be used to support the chain of assessment models for the entire radionuclide release pathway from the dissolution of SNF or waste forms to the surrounding. Further, each NA study review has been rearranged as a standard review template including SA relevance, NA study limitations, assessment of the uncertainties based on the qualitative and quantitative information, and key literature links with public communication. Also the concept of information pyramid has been developed, which can become a useful means for considering questions and issues required to be addressed to the public. The useful data from NAnet project have been assembled using a simple referencing scheme, allowing safety assessors and specialists to quickly find the interesting analogues [40].

In Spain, various NA projects were conducted under the leadership of ENRESA. At the ninth Natural Analogues Working Group (NAWG) Workshop [44], Pedro Hernan of ENRESA published a report on its three major NA projects (MATRIX, ARCHEO, and BARRA). MATRIX [45, 46, 47, 48] was conducted at Mina Fe site, indicating the recent (1–3 Ma) oxidation state of pitchblende near field, the retention of reducing conditions at 20 m depth at a fractured bedrock, and the coprecipitation of U(VI) with Fe(III). The Center for Nuclear Waste Regulatory Analyses (CNWRA) observations in Pefia Blanca also support the results of this NA study. The ARCHEO project focused on the corrosion process and rate in archaeological materials buried for thousands of years. The BARRA project investigated the thermal and geochemical effects of clay barriers in southern Spain and was conducted on the long-term effects of several specific processes on the performance of bentonite barriers in SNF DGD repository. Three different geological conditions have been identified in the bentonite deposits of Cabo de Gata, which may represent a few of the potential evolutionary processes expected from buffers in a DGD repository [49]. One of the bentonite alterations is related to the effect of temperature rise caused by the intrusion of volcanic dome crossing the bentonite deposit. Another alteration can be caused by salt effect of seawater diffusion through bentonite owing to marine invasion after the bentonite formation. The other alteration process is considered the effect of interaction with salt water because of seawater aerosols. The first process can be considered NA to the heating the bentonite barrier by waste heat, while the other two processes can be considered NA to high-salt groundwater (or brine) interacting with the bentonite barrier. Two

Table 3. Summary of disposal system and NA Study in Finland, Canada, the U.S., and Spain

Country	Disposal system	NA study
Finland	Multi-barrier system (KBS-3) Olkiluoto site Crystalline bedrock	• General approach based on geology, hydrochemistry, rock-mechanics, metal corrosion, and microorganism fields • Evolutionary processes including climate change and glacial waster • Publication of Complementary Considerations report in safety case
Canada	Multi-barrier system Crystalline & Sedimentary bedrock	• Natural basis to support the SA and PA of the disposal system design • NA study in the Cigar Lake as a NA scenario with extreme design surrounded by damaged barriers • Release of radioactive nuclides and uranium ore • Identification of defects in thermodynamic database for verification of SA and PA models
U.S.	Multi-barrier system Yucca Mountain site Unsaturated zone High temperature bedrock Social decision after 300 years for permanent disposal	• Consideration of disruptive scenario (tectonic and volcanic activity) around Yucca Mountain • Consideration of higher temperature as a similar condition around waste disposal container and SNF • NA data of time-temperature ranges for repository conditions (in application field and in near-field area)
Spain	Multi-barrier system Crystalline and granite bedrock	• Vast systematic analysis and collections of NA studies (CSN NAA) • Documentation of catalogs, references on NAA and SA, and illustrative synthesis for the public • Review collection of NA studies and radioactive nuclide movements • Expansion of NA study domain into geosphere-biosphere (NAnet) • MATRIX, ARCHEO, and BARRA projects

other bentonite deposits, Morrén de Mateo and Cala de Tomate, were considered to be potentially affected by thermal contact metamorphism by volcanic intrusion. On the other hand, Cortijo de Archidona and San José were selected for salinity and salt water effects.

6. Conclusion and Discussion

Several countries with advanced disposal technology have been conducting NA study to improve the reliability of the long-term safety for their own disposal systems. In NA studies, first, analogues substances and study sites are selected for each component of the disposal system, and NA information is obtained using investigation and analysis of the long-term alteration process of each target analogue, which is used to predict the long-term safety of DGD system. In the case of Korea, although DGD system and safety case have actively been developed for a long time, NA national R&D program was just launched for the first time 2021 and the role and strategy of NA program are required to assist the safety case in the DGD system. Thus in this study, we reviewed some cases of NA programs in advanced countries for HLW disposal. We examined the differences among them and their roles in reflecting the country's own disposal repository design for Finland, Canada, the United States, and Spain. A legal basis and roadmap of NA studies in advanced countries were also described.

6.1 Summary of NA Study by Country

Data derived from NA studies in the mentioned countries are directly or indirectly linked to the PA and SA of the disposal system. This connectivity appears clearly when examining the characteristics and application of NA information. When some of NA data are directly used, the effect on prediction model of the long-term safety model of the disposal system is clearly evaluated. However, others are indirectly used as supplementary evidences to be included in the safety case report and as communication materials to the public.

Disposal systems and NA study by country were briefly summarized in Table 3. Finland's disposal program and her NA study are expected to be useful for the Korean reference HLW disposal system because crystalline bedrock has been considered as HLW disposal site in both Finland and Korea. Finland is constructing a DGD repository using the KBS-3 concept and will be the first in the world to operate a permanent DGD facility. The general NA study data in Finland were investigated based on the geology , hydrochemistry, hydro-geochemistry, and rock-mechanical field at the repository site. A complementary considerations report to support long-term safety was included as part of the safety case, describing various evidences to explain the safety of storage disposal over thousands of years. Canadian NA study provided a natural basis to supplemental support for the SA and PA of the disposal system design through the configuration similarity between the uranium ore in Cigar Lake and the artificial DGR system. Moreover, NA information on radionuclide transport behavior in the groundwater in Cigar Lake was used to verify prediction model, identifying defects in the current thermodynamic database used in safety case model. On the other hand, the United States was oriented towards a unique NA study direction, which places importance on temperature-dependent behavior in HLW disposal facility design. Also, these high temperature curves are typically expected to be similar to those observed around waste disposal containers. Finally, Spain is the only country in the world to implement a state-owned nuclear industry policy and has already decided to directly dispose the SNF and radioactive waste. Various NA programs in Spain had been led domestically and internationally. As a result, a vast collection of NAA studies and 19 major SA studies was published, including NAA catalogs (CSD 1+D document), greater than 2,000 references on NAA and SA, and illustrative synthesis of the study for the unprofessional public.

6.2 Implication to Korea NA Study

In Korea, where the concept of HLW disposal has not been determined yet, it would be desirable to pursue a general NA study approach similar like that in Finland. However, NA study should reflect the characteristics of the domestic disposal concept and the environmental conditions of the repository site, so it is judged that continuous NA study should be performed from the stage of development of the disposal program to that of repository operation. Domestic NA study needs to consider its strategy and direction using the case of NA study in the above countries as a precedent.

First of all, like the Spanish Na study case, it is necessary to actively participate in a joint research on NA study overseas, and to organize a research group domestically. NA study on several kinds of environmental conditions should be essential to study the safety of a disposal system that will undergo various long-term evolutions over a long period of time. Thus it would be the best strategy to conduct diverse long-term alteration researches as efficiently as possible through sharing information with global research groups, because each nation has different environments geochemically, geologically, hydro-geologically, and climatologically. So it is necessary to actively join in internationally pre-configured NAWG and the others, and more practical information can be acquired and utilized quantitatively and qualitatively.

In particular, in domestic NA study on the alteration process of metal container materials, cooperation in the field of archaeology is essential and it is necessary to convey the need for research on the environment condition around natural and archaeological analogues and to expand the cooperation opportunities. Because the most important thing on NA study is to secure natural and archaeological analogues and to acquire research sites around them, and

Table 4. Major research tasks of KAERI NA study

Component /Process	Research tasks
Buffer	• Research on the buffer properties in domestic and overseas countries • Identification and analysis of alteration characteristics according to surrounding conditions (thermal, hyper-alkaline, and saline effects) • Establishment of a conceptual model for alteration mechanism
Canister	• Research on the corrosion properties of archeological metals • Identification of corrosion characteristics of metal artifact by period/burial environment (redox, hyper-alkaline, and saline effects) • Analysis of corrosion limitation of archeological metals • Establishment of a conceptual model for metal corrosion
Uranium	• Research on the characteristics and origin of uranium ore • Analysis of uranium migration with groundwater flow • Analysis of geochemical and biochemical reactions • Establishment of a conceptual model for the retardation of uranium migration
Database system and the application	• Development and construction of DB system for NA information data • Development of characterization and utilization of NA information • Establishment of application plans for safety case

most archaeological communities have very exclusive access to them.

As seen in the case of establishing a NA information system in Spain, domestic NA study should also focus on developing systems to improve social acceptance of disposal facility safety, because it is expected that social acceptance will be the most difficulty for construction of waste disposal system. These effort to establish NA information system should be conducted in two ways to enhance the reliability of the disposal facility. As a hardware system, a NA study research center is the first way, where people can build trust in the safety of the disposal system through visual samples (natural and archeological analogues) acquired in NA study. On the other hand, it is also necessary to construct software database system that allows the developers to easily find NA study information and to utilize it for facility design and safety case. To this end, an integrated database system to reflect domestic conditions should be established for domestic geological distribution, groundwater characteristics, natural and archaeological analogous and environmental conditions with the perspective of disposal systems and NA study as in the case of US.

In this study, it was found that NA study programs in foreign countries have been conducted on the leadership of nuclear regulatory agencies (CNSC, NRC, CSN, STUK). In the case of Finland and Spain, the operator (POSIVA and ENRESA) of the disposal facility along with the regulatory agency have played an important role in NA study. Domestic NA study system should also be established based on the organic cooperation with nuclear regulatory agency, disposal facility operator, and research institute forwards.

Lastly, the NA research tasks to be achieved by KAERI were briefly summarized in Table 4. Although the results of this study correspond to overseas cases with different environmental conditions, they can be used as important information to establish various research strategies and to strengthen the NA study environment for domestic HLW disposal system.

Acknowledgements

We would like to thank YeoJin Ju of Korea Atomic Energy Research Institute (KAERI), South Korea for assistance in investigating the Canadian case. This work was supported by the Institute for Korea Spent Nucler Fuel (iKSNF) and National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT, MSIT) (No. 2021M2E1A1085186).

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