Waste management strategies and disposal concepts for spent nuclear fuel around the world

Stratégies de gestion des déchets et concepts d'élimination des déchets nucléaires dans le monde

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ABSTRACT: The final safe disposal of spent nuclear fuel is one of the major challenges of our time. Nuclear powered nations are actively developing long-term waste management strategies and disposal concepts for their spent nuclear fuel, and high-level waste resulting from reprocessing. Direct disposal and reprocessing are the waste management strategies currently being adopted by countries around the world. In November 2015, the Finnish government granted the construction license to build a permanent deep-rock geological repository for the final safe disposal of spent nuclear fuel in Finland; the first of its kind. Of other countries that have embraced the direct disposal concept, only Sweden and France have made significant progress in site selection and the development of their own disposal concepts. Canada and the UK have invited communities to volunteer to host a geological repository before the final screening of site selection process. Many other countries are in the preliminary stages of developing their own waste management strategies and disposal concepts while a few large nuclear nations such as Germany and the USA are facing political and societal opposition on their adopted waste management strategies. This paper compiles information on the long-term disposal strategies of spent nuclear fuel that are adopted or being considered as potential strategies worldwide.

KEYWORDS: nuclear waste; waste management; geological repository; direct disposal; KBS-3V;

RÉSUMÉ : L'élimination définitive en toute sécurité du combustible nucléaire irradié est l'un des principaux défis de notre époque. Les pays détenant l'arme nucléaire sont activement impliqués dans le développement de stratégies de gestion des déchets à long terme et des concepts de disposition pour leur combustible irradié et des déchets de haute activité résultant du retraitement. Le rejet direct et le retraitement sont les stratégies de gestion des déchets actuellement adoptées par les pays du monde entier. En novembre 2015, le gouvernement finlandais a accepté le permis de construire pour la construction d'un dépôt en couches géologiques profondes pour l'élimination sûre et définitive du combustible nucléaire irradié en Finlande; le premier ce type. D'autres pays ont adhéré au concept d'élimination directe, seule la Suède et la France ont nettement progressé dans la sélection des sites et dans le développement de leurs propres concepts d'élimination du combustible nucléaire irradié. Le Canada et le Royaume-Uni ont invité les collectivités à se porter volontaires pour accueillir un dépôt géologique avant le processus de sélection des sites. Beaucoup d'autres pays sont à l'étape préliminaire de l'élaboration de leurs propres stratégies de gestion des déchets et des concepts d'élimination alors que quelques grandes nations détenant l'arme nucléaire comme l'Allemagne et les États-Unis sont confrontées à l'opposition politique et sociétale sur leurs stratégies de gestion des déchets. Ce document rassemble des informations sur les stratégies à long terme d'élimination du combustible nucléaire irradié qui sont adoptées ou envisagées comme des stratégies potentielles dans le monde.

KEYWORDS: déchets nucléaires; gestion des déchets; dépôt géologique; élimination directe; KBS-3V;

1 INTRODUCTION

Global need for nuclear energy has led to one of the most challenging issues of this century, the final safe disposal of spent nuclear fuel (SF). Despite the efforts to find alternative renewable energy sources, the projection for SF production is constantly increasing. This means that the legacy of nuclear power and SF is to continue for a foreseeable future. Some of the nuclear powered nations have already made their long-term nuclear waste management strategies, while the others are yet to decide on this. To date, many countries are considering the option of safely disposing their SF in deep ground (rock or clay) geological repositories, also known as "geological vaults" (Sinnathamby et al. 2015). In 2015, Finland has become the first country to implement the construction of such a geological repository in crystalline bedrock of Olkiluoto Island, at a depth of approximately 420 metres.

This paper summarizes the waste management strategies and disposal concepts adopted or being considered by various nuclear waste management regulators and companies around the world to date.

2 WHAT IS NUCLEAR WASTE

In a broader classification, wastes that arise from nuclear power plants can be categorised into low-level (LLW), intermediate-level and High-level (HLW) wastes. LLW is comprised mainly of lightly contaminated items used during the operation of power plants such as tools and clothing. Radioactivity of intermediate level waste is slightly higher than that of LLW and is mainly composed of materials within the reactor such as filters, steel components and other parts. Some effluents that result from reprocessing are also categorised as intermediate level waste. HLW is mainly the SF that is left over after it has spent about three years in the reactor, and also some of the wastes that arise from reprocessing of SF (Sinnathamby, 2012).

Even though the volume of SF amounts for only 3% of the total waste produced from nuclear power generation, it accounts for 95% of radioactivity. The level of potential hazard (i.e. radioactivity) of nuclear waste diminishes with time; however, it could take up to several hundreds of thousands of years. Thus, nuclear waste requires a complete isolation from the biosphere during this entire period. The following section discusses various nuclear waste management strategies, mainly for SF and other HLW, that are adopted or being considered around the world.

3 NUCLEAR WASTE MANAGEMENT STRATEGIES

To date, the waste management strategies adopted or being considered for adoption worldwide for the long-term management of nuclear waste can be categorised into two. The first one is direct disposal (DD) technique in which the SF is removed from the core reactor and simply considered as a waste; and in the other, the SF is reprocessed (RP) and materials such as uranium and plutonium are extracted for reuse as new fuel (Allan & Baumgartner, 1997). RP also produces HLW that requires the same treatment as the SF that arises from DD (Fig 1).

Regardless of the strategies that are adopted, SF first needs to be stored in wet pools for initial cooling and radiation shielding. Wet pools are generally located within the premises of the reactor facility so that the fuel can be stored directly after the removal from the core-reactor. The duration of this initial storage could go up to tens of years depending on the storage capacity of the pools, but a minimum period of 9 to 12 months is needed for sufficient decaying of heat and radiation (world-nuclear.org, 2016).

After the initial cooling, the fuel that requires reprocessing is transported to RP facilities and once again stored in buffer storage pools before being processed. On the other hand, the fuel classified for DD may remain stored in the original reactor storage pools. The DD fuel can also be stored in separate 'Away From Reactor' (AFR) fuel storage facilities, which could be either part of the reactor site or another dedicated site.

Even though the most widely used storage technology is wet storage, some countries like Switzerland and USA are also employing dry storage technology which includes modular vaults, soils and casks. Dry storage is generally accepted as more economical in the long-run despite its low heat dissipation capability (world-nuclear.org, 2016).

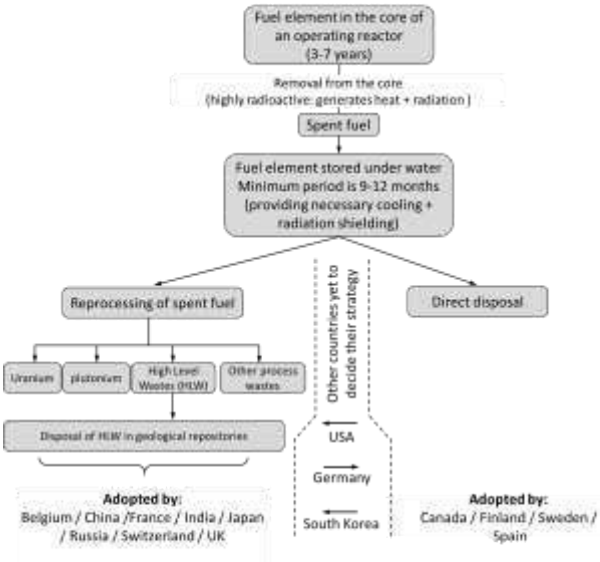

Fig. 1. Nuclear waste management strategies around the world.

During the reprocessing of SF, the resulted liquid HLW from RP facilities is first solidified by vitrification (i.e. a process which involves HLW melted together with glass materials in order to be absorbed into a glass structure at high temperatures in the range of + 1000°C) and sealed in metal containers and subjected to controlled cooling before moving them to a final disposal site (Baehr, 1989).

4 DISPOSAL CONCEPTS

Currently, the most developed concept for the final safe disposal of nuclear waste is to store them in deep geological formations. The nuclear waste is encapsulated in metal canisters and stored safely several hundreds of metres deep in stable geological formations that assure intact storage for the next hundreds of thousands of years to come. The selected geological formation must provide stable thermal-hydro-mechanical-chemical (THMC) environment at the repository depth. Typically the geological formation should be mechanically stable and water tight (very low to no groundwater movement), and should also possess stable geochemical conditions of the groundwater (Sinnathamby et al. 2014a).

Once the emplacement of fuel canisters are completed, the tunnels (voids) in the repository are backfilled with appropriate materials that provide water tightness and additional mechanical stability to the tunnels and to the repository as a whole. The tunnel backfill forms a multi-barrier, together with buffer material that directly surrounds the fuel canisters and ensures that the failure of a single barrier does not jeopardise the integrity of the entire multi-barrier system (Sinnathamby et al., 2014b). The technological development in this concept is well advanced over the past few decades through research laboratories in Sweden, Switzerland, Finland and France. Research and development activities in deep-geological repositories are continuously advancing and would be incorporated in the final design of the repository.

Deep-geological repositories have multiple levels of barriers. The waste matrix itself (solid fuel pellets and fuel-rod cladding) is the first layer of this barrier. Secondly, the engineered multi-barrier system often composed of metal canisters (usually copper canisters that contain the SF or HLW) and several other clay based materials (bentonite and other swelling clays) as buffers and backfills. The host geological formation (crystalline rock / clay or other mineral layer) provides the ultimate shielding (Sellin & Leupin, 2013).

No geological repository for SF or HLW has yet been built, but there are a few countries that have finalised their site selection process. In 2015, Finland has become the first country to obtain a construction license for a deep rock geological repository at a depth of approximately 420 m below the ground level in crystalline bedrock. Several other countries have made significant progress on developing their long-term nuclear waste management strategies. The following section compiles the available information and latest updates on disposal concepts and different nuclear waste management strategies adopted or being considered for adoption around the world.

4.1 Europe

4.1.1 *Finland and Sweden*

Finland and Sweden have opted for DD and much of the development of the final disposal concept "KBS-3" has been jointly conducted by the Swedish nuclear fuel and waste management company SKB and its Finnish counterpart Posiva Oy. In the KBS-3 concept, the SF is encapsulated in copper canisters with an iron insert. The iron insert provides mechanical stability and the copper shell provides corrosion protection. Each canister is about 4.8 m long, has a diameter of 1 m, and weighs around 25 tonnes. The canisters will be stored in tunnels (KBS-3H) or in deposition holes (KBS-3V) at a depth of around 400 – 700 m in crystalline bedrock. The void between the bedrock and the canisters will be filled with compacted bentonite clay, known as buffer (Hedin, 2004).

Finland is the first country to begin construction of a final repository for SF and embracing the KBS-3V disposal concept. Olkiluoto, located in the western coast of Finland in the municipality of Eurajoki, hosts the repository. Construction of an underground research laboratory (commonly referred to as URLs), ONKALO, was started in 2004 and the main purpose of this test facility was to characterize the geology of the crystalline rock formation for hosting the repository (Posiva, 2003). Following a positive review from the Finnish radiation safety authority (STUK), the Finnish government granted the construction license for the repository in 2015. The repository is expected to start its operation in 2020s and will have capacity to house around 6500 tonnes of SF from Finland.

The Swedish Nuclear Fuel and Waste Management Company SKB, a joint venture of nuclear power companies in Sweden, is responsible for the management and disposal of all nuclear waste produces from Sweden. After decades of research, in 2009, Forsmark in Östhammar municipality was chosen to host the geological nuclear waste repository supported by an extensive research programme, including the Äspö Hard Rock Laboratory. An application to construct a geological nuclear waste storage facility has been submitted to the Swedish Radiation Safety Authority (SSM) and to the Land and Environment Court to build the SF Repository in Forsmark in March 2011and the outcome expected in 2017 (SKB.com, 2015). In June 2016, SKB claimed that the Swedish Radiation Safety Authority has endorsed their application in its statement submitted to the Land and Environment Court (SKB.com, 2016). The repository is expected to be filled around 2050, and the different sections of the repository can then be fully sealed.

4.1.2 *France*

Andra, the National Agency for Radioactive Waste Management in France, has finalised the location for the Centre Industriel de Stockage Géologique (Cigéo) repository near Bure in the Meuse/Haute Marne area. The site will be a part of Meuse/Haute Marne Underground Research Laboratory (URL) run by Andra. The proposed 500 m deep geological repository will be in a natural clay layer, unlike the repositories in Finland and Sweden. Research studies are being conducted by Andra in order to assess the suitability of the geology in this site (Andra, 2005). Submission of the construction license to build the Cigéo facility is expected in 2017, and upon approval, the construction will start in 2020. The pilot phase of disposal is expected around 2025. Some 2700 cubic metres of HLW and about 40,000 cubic metres of long-lived intermediate-level radioactive waste are to be disposed in the Cigéo facility (Andra, 2014).

4.1.3 *Germany*

Gorleben, in the northern state of Lower Saxony, had been under discussion as a potential site for the final disposal of SF in Germany (Flynn et al., 1992). However, the site has seen numerous anti-nuclear demonstrations. Following the 2011 Fukushima nuclear reactor disaster in Japan, Germany decided to terminate the operation of its all eight remaining active reactors by 2022. Such a tight timeframe lead to a pressing situation in order to find a safe site for the final geological repository for SF and the site selection process is once again has resumed.

4.1.4 *United Kingdom*

The SF from UK's power plants is stored in Sellafield, Cumbria. An attempt to build an underground research laboratory for possible deep geological repository has been voted out by the Cumbria's county council in 2013. Since then, the Radioactive Waste Management (RWM), a subsidiary of Nuclear Decommissioning Authority (NDA), has been working closely with communities around the UK to help build understanding and awareness of the geological disposal concept. NDA believes that this would help to overcome the societal resistance in site selection process. It is anticipated that the initial screening for a suitable site location will be completed in 2017 (NDA, 2016).

4.1.4 *Switzerland*

Nagra, the company responsible for the nuclear waste management and disposal in Switzerland operates the Grimsel hard-rock laboratory in the Swiss Alps since 1983. The laboratory consists of a kilometre-long tunnel, which hosted several full-scale tests. The Full-scale Engineered Barrier Experiment (FEBEX) is one of such tests carried out here. FEBEX aimed at enhancing the know-how of the near-field THMC activities in typical clay buffer that protects the fuel canisters. The FEBEX study has been conducted over 18 years, initiated by the Spanish nuclear waste company Enresa; however, since 2008 it has been a consortium formed by SKB (Sweden), Posiva (Finland), Ciemat (Spain), Nagra (Switzerland) and Kaeri (Korea). In FEBEX, two canisters with steel heaters at about + 100°C, representing real-scenario fuel canisters, were horizontally embedded in the crystalline bedrock of Grimsel and enclosed with bentonite buffer. Numerous temperature, humidity, total pressure, movements and portal pressure sensors were installed to acquire direct measurements of the clay buffer, bedrock and the heaters. One of the canisters was dismantled after five years, and the other in 2015. Several hundreds of bentonite clay, cement and rock samples were taken and being tested for various properties and performance analysis (Alonso et al., 2005).

4.1.5 *Belgium*

Belgium initially reprocessed its SF at the COGEMA RP plant in La Hague, France. However, a resolution passed in the Belgian parliament in 1993 brought the end of RP and since then the SF is stored at reactor sites awaits final disposal. Belgium has been studying possible geological repository for its vitrified HLW and SF in a 90 m thick Boom Clay reference formation at about 200 m beneath the ground level at Mol-Dessel nuclear site. An underground research laboratory was established at the Mol site in 1984 and since then the host-formation has been characterised extensively (world-nuclear.org, 2016).

4 .2 North America

4.2.1 *United States*

Due to socio-political reasons, the proposed deep geological repository project at Nevada's Yucca Mountain has been abandoned in 2010. The US Department of Energy (DOE) currently adopts a 'consent based' approach which aims to build support and awareness at the local and state level prior to the designation of a site location for the final repository construction (DOE, 2016).

4.2 2 *Canada*

The Canadian Nuclear Safety Commission (CNSC) is the nuclear regulator in Canada and responsible for the licensing of geological disposal facilities for radioactive wastes in Canada. Canada's R&D programmes on long-term geological repositories date back to 1978. At the moment, two different long-term radioactive waste management initiatives are proposed; one for low and intermediate waste by the Ontario Power Generation's Deep Geological Repository (also known as OPG DGR) and the other for SF by the Nuclear Waste Management Organisation Adaptive Phased Management Approach (NWMO APM). It is expected that these two initiatives may lead to deep geological repositories. A location at Bruce nuclear site in Tiverton, Ontario has been selected for the OPG DGR and the repository will be located in clay-rich limestone formation. The NWMO is conducting a site selection process in which an informed and willing host for the project will be identified. The site selection process was initiated in mid-2010 but a final location has not yet been decided. Upon the selection of final location, a ten-year period is expected for the construction of the facility (NWMO, 2010).

4 .3 *Asia*

4.3.1 *China*

The site selection and evaluation for a geological repository in China has been underway since 1980s and a permanent deep geological repository was required by law in 2003 (world-nuclear.org, 2016). Three candidate sites in the Beishan area of Gansu province (near the Gobi desert) are being researched extensively for their geological conditions and suitability to house a repository for China's vitrified high-level waste. The final site selection is expected to be completed in 2020s. The proposed repository concept is a shaft-tunnel model, located in the saturated zones of granite formation at a depth of around 500 m below the ground level. Upon the successful selection of final site, an underground research laboratory will be built and the construction of final repository is expected in 2040s.

4.3.2 *Japan*

Following the meltdown of three reactors at the Fukushima power plant in Japan during the 2011 tsunami, all 43 of its operational reactors have been shut down for safety assessment. The aftermath of the tsunami raised societal concerns on the fate of Japan's nuclear future and also about its stored HLW.

The Nuclear waste Management Organization of Japan (NUMO) is currently engaged in the preliminary stage of site selection process for an Underground Investigation Facility (UIF) which would later be a part of the final geological repository. NUMO is currently conducting open solicitation with municipalities around the country and seeking potential areas to carry out feasibility studies for site selection. Once the solicitation confirms that the site is free of volcanic activities, active faults and other geological phenomena, the selection will then proceed based on a three-stage process, namely; Preliminary Investigation Areas (PIAs), selection of Detailed Investigation Areas (DIAs) and ultimately, the selection of a final repository construction site (NUMO, 2016).

5 RECENT ADVANCEMENT IN NUCLEAR TECHNOLOGY AND WASTE MANAGEMENT

Recent years have seen a number of ground-breaking researches in nuclear power generation and also in reprocessing of SF. Researchers in the ITER project are attempting nuclear power generation by fusion in Provence, France. The principle of fusion technology is to trap plasma in a huge magnetic ring and force heavy hydrogen isotopes to fuse together. It is expected that this fusion would result in releasing enormous amount of energy, anticipated four times higher than the energy released during splitting of uranium atoms in conventional (fission) reactors (Fiore, 2006).

Construction of the world's largest TOKAMAK, a magnetic fusion device that is designed to harness the fusion energy, is underway in the ITER project and is expected to become operational 2025. ITER scientists claim that the radioactive waste produced from the fusion needs only few decades to decay its radioactivity in contrast to the wastes from traditional fission reactors that needs several hundreds of thousands of years to become harmless. Therefore, such a credible timescale for the fusion waste can be easily dealt with when compared to its fusion waste. A successful implementation of the fusion technology could drastically change the current radioactive waste management strategies and final safe disposal of nuclear waste.

6 SUMMARY

This paper summarized the waste management strategies and disposal concepts adopted or being considered for adoption by various nuclear waste management regulators and companies around the world to date.

Progress on nuclear waste disposal in the coming years would be crucial as many countries are approaching their final site selection process for geological repositories and some await the decision on their construction license applications. A high success rate on these two key milestones of the whole nuclear waste disposal cycle could change the socio-political outlook positively in other countries and may lead to a much smoother decision making in the site selection process for a final geological disposal facility.

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