A RESILIENT BACK-END FUEL CYCLE FOR MANAGING SPENT FUEL FROM NUCLEAR POWER REACTORS

J. S. CHOI
Lawrence Livermore National Laboratory (retired),
C USA
Email: jorshan1@gmail.com

Abstract

Fukushima drew attention to the problem of "what to do with the spent nuclear fuels that are generated, stored, accumulated, or "stranded" at nuclear power plants?" This problem is not confined only to Fukushima, Japan, but is faced by all nuclear power programs. The debate on spent fuel management has centered on what to do with plutonium, a by-product of nuclear fission. Countries concerned with the possibility of plutonium misuse prefer a once-through approach including the direct disposal of spent fuel, while others considering plutonium as an energy resource advocate reprocessing and recycling.

Regardless of how spent fuel is managed, final disposal of spent fuel and/or radioactive wastes is necessary. The challenges with disposal are complex involving technological, political, and societal aspects of finding appropriate disposal sites. An example of this difficulty was the US repository program at Yucca Mountain, which was abandoned in 2009 after 20+ years of developmental effort. Despite the challenges, Finland and Sweden succeeded in locating their disposal sites and continue to develop repositories to dispose of their respective spent fuel.

In future global nuclear energy expansion, many emerging nuclear countries would like to have an assurance of fresh fuel supply, free of disruptions to fuel their reactors. Such assurance is emboldened by the IAEA fuel banks in Ust-Kamenogorsk, Kazakhstan and Angarsk, Russia. For the back-end it is equally important to provide assurance that the spent fuel could be managed properly. Such assurance would include spent fuel take-back/away, centralized/regional storage, advanced processing technologies, and multinational repository. These back-end provisions by cooperative consortia and endorsed by IAEA are essential in forming a resilient fuel cycle, which would decouple the power generation from long-term spent fuel management, enhance nuclear safety, reduce security and proliferation risks, as well as provide flexibility and retain options for future strategic changes.

A resilient back-end fuel cycle requires innovative technologies, which include novel material development for transportation, aging, and disposal (TAD) containers; proliferation-resistant reprocessing; and alternate disposal concept such as deep-bore holes. It also needs cooperative institutional frameworks to facilitate spent fuel take-back/away; centralized/regional storage; and multinational repository. This paper examines the technological and institutional requirements and shows how the resilient fuel cycle could provide flexibility and preserve options for spent fuel management, as well as support for future global nuclear energy expansion.

1. INTRODUCTION

Spent nuclear fuel discharged from nuclear power reactors are presently stored in wet pools and/or in dry casks, at-reactor and/or away-from-reactor sites. The accident in Fukushima in 2011 drew an attention to the nagging problem of "what to do with the light-water reactor (LWR) spent fuels, which are generated, stored and accumulated at nuclear power plants (NPPs)?" Technically, geologic disposal of spent fuel/high-level radioactive wastes (HLW) is a robust solution, but institutional issues such as finding suitable disposal sites and public acceptance must be resolved. Presently, only a few countries reprocess their civilian LWR spent fuel, notably France and Russia. No country has yet operated a geologic repository to dispose of civilian spent fuel or HLW. As a result, the management and disposal of spent fuel and HLW are viewed as the Achilles' heel of nuclear power.

1.1 Spent Fuel Arisings in the US and East Asia

As an example, Fig. 1 shows the spent fuel inventory in the US and East Asian nuclear power programs. The inventory is estimated based on that in 2010 and that generated by the projected growth of nuclear power in these programs to 2020 and 2030.

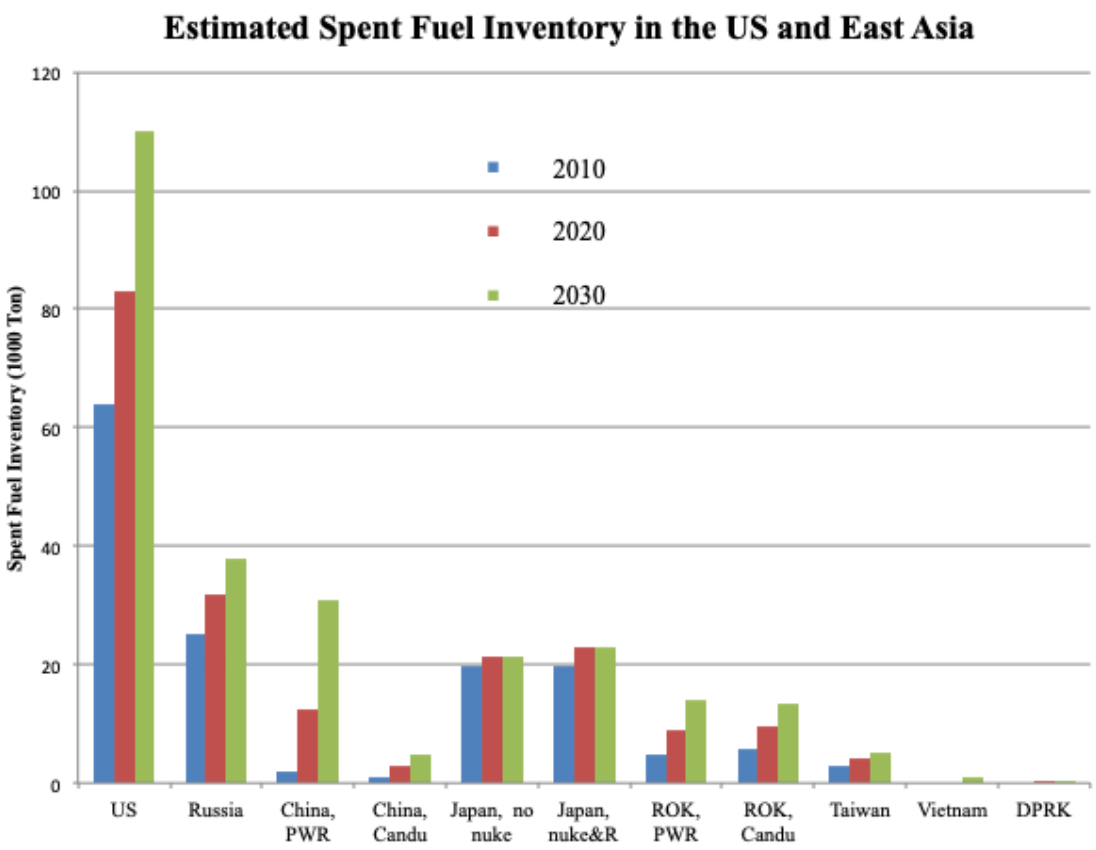

FIG. 1. Estimated Spent Fuel Inventory in the US and East Asia.

Figure 1 indicates that in 2010, the US had about 63,900 tons of spent fuel from light-water reactors (LWR), accounting for more than 33% of global used LWR fuel inventory. More than 95% of the US NPPs are >20 years or older and many are operating with their life-extension licenses. Assuming a limited growth of nuclear power, the spent fuel inventory from existing US reactors is expected to reach about 83,000 and 110,000 tons by 2020 and 2030, respectively [1].

In Russia, spent fuel from VVER-440, BN-600 fast reactor, and naval reactors are reprocessed at the Mayak RT-1facility. Russia had 25,100 tons of spent fuel in 2010. Based on a modest growth of nuclear power in Russia, the spent fuel inventory is expected to increase to about 32,000 and 38,000 tons by 2020 and 2030, respectively.

The nuclear energy programs in East Asia (China, Japan, ROK, and Taiwan) account for 19% of global spent LWR fuel inventory in 2010. China's spent fuel inventory in 2010 was relatively small at 1,900 tons, but is expected to grow rapidly to ~12,000 and ~31,000 tons in 2020 and 2030, respectively, based on its expanding nuclear power program to ~60 and ~200 GW in 2020 and 2030, respectively. Besides PWRs, China also operates 2 CANDU reactors which each produces roughly 8 times more spent

fuel in tons than a PWR of the same power. The spent CANDU fuel inventory would increase from 950 tons in 2010 to 2,850 and 4,750 tons in 2020 and 2030, respectively.

Spent fuel in Japan, ROK, and Taiwan are US-obligated[1]. Japan's future trends of spent fuel inventory is uncertain due to the unknown numbers and timing of the currently-shut-down nuclear power plants that would be allowed to restart, and the uncertain future of Japan's reprocessing at Rokkasho. Under two scenarios (a no-nuke/no-reprocessing and a 80%-nuke with reprocessing), the Japanese spent fuel inventory could be capped at ~21,500 tons for the first scenario, and to ~22,500 tons for the second, as shown in Fig. 1.

The ROK's spent PWR fuel inventory would increase from 4,900 tons in 2010 to about 8,800 and 14,000 tons in 2020 and 2030, respectively. Its spent CANDU fuel inventory would also increase from 5,900 tons in 2010 to about 9,700 and 13,500 tons in 2020 and 2030, respectively [2, 3]. As Taiwan is phasing out its nuclear power program, its spent fuel inventory increases modestly from 3,000 tons in 2010 to about 4,300 and 5,000 tons in 2020 and 2030, respectively. Spent fuel inventory in other East Asian countries (DPRK, Vietnam, etc.) should be small, if any before 2030.

2. DRY CASK STORAGE

Dry-cask storage is viewed in the US as a critical bridge between spent fuel produced at NPP sites and a long-term approach to radioactive waste disposal. As at-reactor pool-storage is saturated or when the reactor is decommissioned, the dry-cask storage system can provide a long-term storage of spent fuel in a safe, secure, cost-effective and flexible manner. Of the 75 reactor sites in the US, 80% have installed the dry cask storage systems [4]. By 2020, all US reactor sites would have dry cask storage of spent fuel.

To enhance the long-term spent-fuel storage in dry casks, novel materials are needed to provide robust corrosion resistance and criticality safety. Neutron-absorbing Fe-based amorphous-alloy coatings have been developed that are more corrosion resistant than other criticality-control materials, including Al-B4C, borated stainless steels, and Ni-Cr-Mo-Gd alloys [5, 6, 7]. The presence of relatively high concentration of boron in these amorphous-alloy coatings not only enhances its neutron-absorption capability, but also enables these coatings to exist in the amorphous state.

A family of Fe-based amorphous alloy powders with very good corrosion resistance have been successfully produced in multi-ton quantities with gas atomization and can be applied as a protective coating with the high-velocity oxy-fuel (HVOF) thermal spray process. One of the most promising formulations within this family was found to be Fe49.7Cr17.7Mn1.9Mo7.4W1.6B15.2C3.8Si2.4 (SAM2X5), which included chromium (Cr), molybdenum (Mo), and tungsten (W) for enhanced corrosion resistance, and boron (B) to enable glass formation and neutron absorption. The use of this neutron-absorbing material to coat the surfaces of the containers and the insider baskets substantially enhances criticality safety for spent fuel insider the transportation-aging-disposal (TAD) containers. Figure 2 shows a half-scale container and a criticality basket were coated with SAM2X5 atomized powders, and X-ray diffraction measurements before and after coating with HVOF thermal spray process.

[1] "US-Obligated spent fuel" – US prior consent rights to reprocessing of spent fuel as a result of the 123-agreements signed by the US and the respective parties.

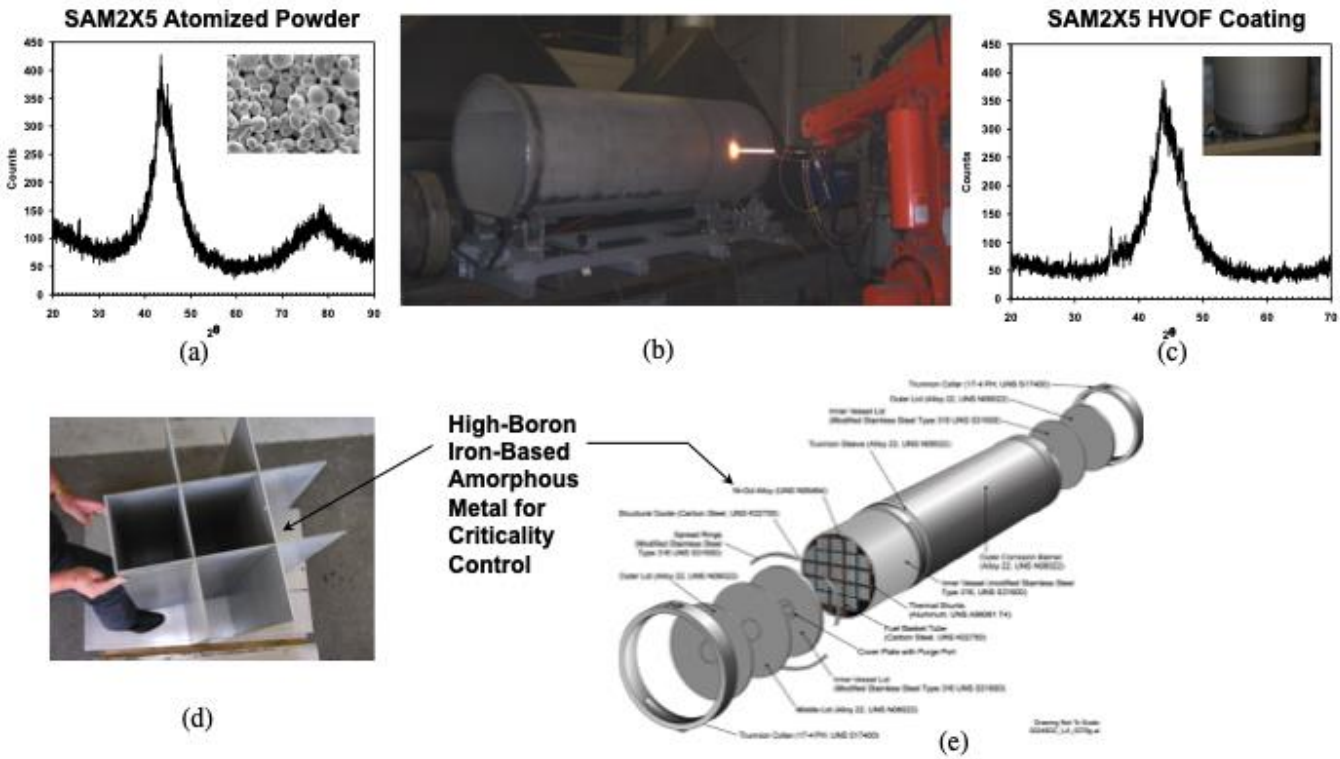

FIG. 2. Coating a half-scale container (b) and a criticality basket (d) with SAM2X5 atomized powders, with X-ray diffraction measurements (a) and (c) before and after HVOF process, respectively, while a schematic of a TAD container is shown in (e).

To study the effects of the amorphous metals under fast neutron and gamma irradiation, series of amorphous alloy melt-spun ribbons, coated plates, and cast ingots were irradiated in the 2MW TRIGA reactor at McClellan Nuclear Radiation Center (MNRC). X-ray diffraction is used to examine these test specimens before and after multiple periods of irradiation experiment to confirm the corrosion resistant performance of the irradiated amorphous metal specimens.

Neutron transmission measurements of the SAM2X5 coated plates were conducted with neutron beams at MNRC. Average measured values of the transmission neutron absorption cross section (Σ) for Type 316L stainless steel, Alloy C-22, borated stainless steel, Ni-Gd alloy, and SAM2X5 coated plate were determined to be approximately 1.1, 1.3, 2.3, 3.8, and 7.1 cm-1, respectively, as shown in Fig. 3.

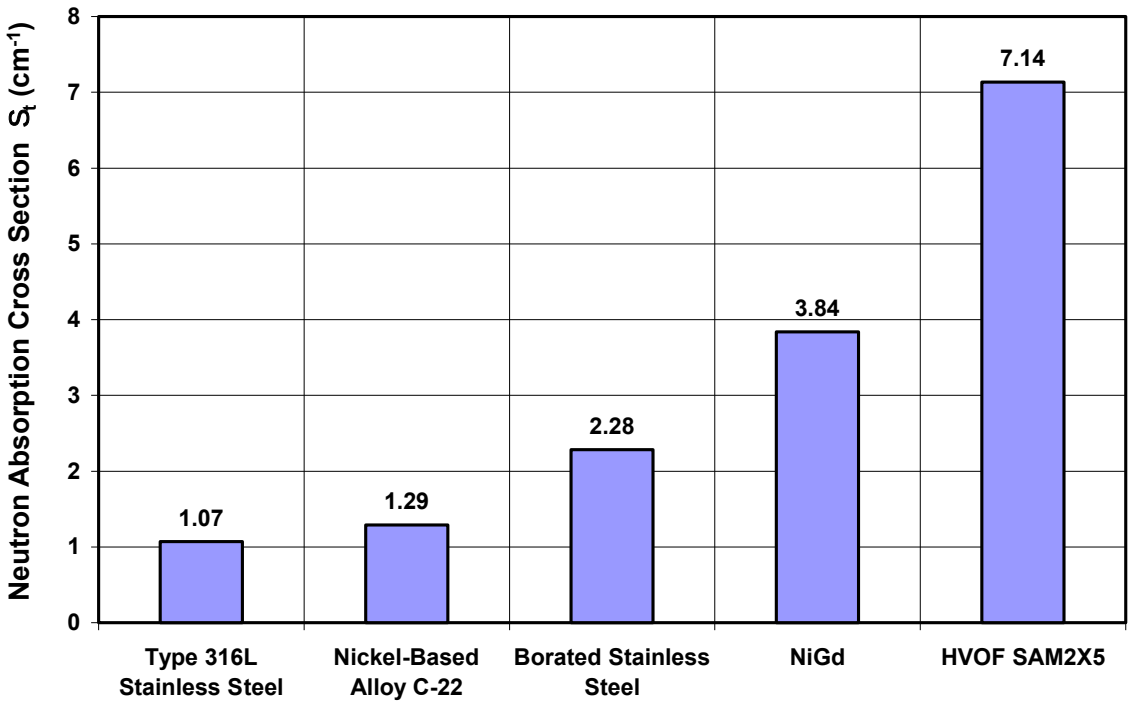

FIG. 3. Neutron Absorption Cross Sections of Various Alloys.

3. MSMNA

In future global nuclear energy expansion, many emerging nuclear countries would like to have an assurance of fresh fuel supply, free of political disruptions to fuel their reactors. The fresh fuel would be guaranteed by market mechanism based on commercial contracts made with fuel-service providers. Such fuel-supply assurance could minimize or eliminate incentives for emerging countries to acquire indigenous enrichment capabilities. Equally important is the ability to provide assurance that the spent fuel could be managed properly. Such assurance would include spent fuel take-back/away, interim storage, advanced processing technology, and geologic disposal of spent fuel and HLW.

For spent fuel/HLW in existing nuclear power programs, the responsibilities of managing and finally disposing of these materials rest upon the owner countries. However, the ability to properly managing spent fuel/HLW is not equal among owner countries (e.g., resources, and finding suitable geologic repositories), a cooperative concept, called multi-site/multi-national arrangement (MSMNA) is proposed here to help manage and dispose of spent fuel/HLW in existing and emerging nuclear programs. It is suggested that the MSMNA would be led by two groups of countries: (1) the major nuclear-power countries, e.g., China, Russia, and the US; and (2) the major uranium producers, e.g., Australia, Canada, and Kazakhstan. It is to the vast interest of these two groups of countries that the spent fuel/HLW are properly managed and disposed of according to good governance and environmental compliance. Figure 4 shows the MSMNA concept.

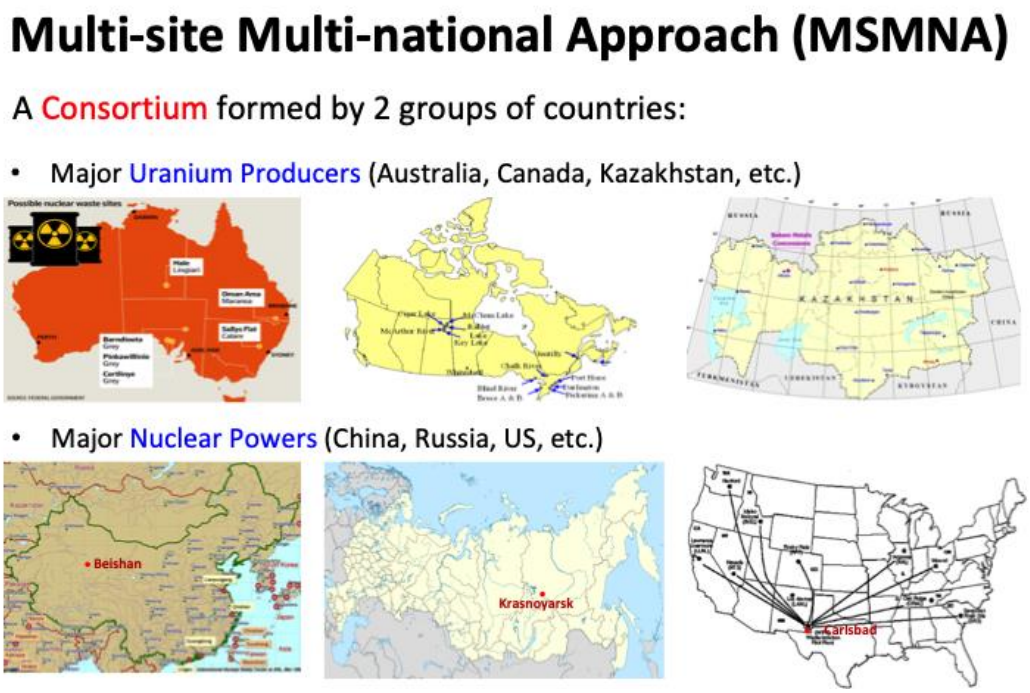

FIG. 4. A MSMNA Concept Proposed for Managing Spent Fuel.

The proposed MSMNA operates somewhat like URENCO's multi-sites/multi-countries control of enrichment enterprise, where three countries, UK, Germany, and Netherlands, each operate an enrichment facility within its border. URENCO is a business, providing uranium enrichment services and at the same time, preventing the spread/proliferation of the enrichment technology. Similarly for MSMNA, the proposed objectives are to (1) construct and operate interim storage facilities at multi-sites within the MSMNA, (2) take-away/back of spent fuel from existing and emerging nuclear programs to one or more of the MSMNA multi-site facilities.

Hosting interim storage and/or repository for other countries' spent fuel and/or radioactive wastes is controversial. There are many social and institutional issues involved, and not to mention that there are laws in many countries prohibiting the import of radioactive wastes. Despite the challenges, the establishment of the proposed MSMNA would provide flexibility in long-term spent fuel management, and allow countries to decouple the power generation from the nuclear back-end. Such decoupling is essential for facilitating a resilient nuclear fuel cycle and supporting an expanded nuclear power future.

4. INNOVATIVE DISPOSAL CONCEPT

Final geologic disposal of spent fuel/HLW is necessary regardless of how spent fuel is managed. The challenges of radioactive waste disposal in mined repository are many, including but not limited to radioactivity and heat, release of long-lived radionuclide, and breaching a mined repository by natural events or human intrusion. In light of these challenges, innovative waste treatment and disposal means (i.e., hot-iso-static compaction and deep geologic boreholes disposal of radioactive wastes) are proposed as alternative to disposing spent fuel in mined geologic repository.

4.1 A Simple Dry Process for Spent LWR Fuel

Adopting from the first few steps of the pyro-processes that include de-cladding, voloxidation, electro-reduction and uranium separation [8], a simple dry process is shown in Table 1. It includes the research and development effort and experience incurred in each step process, as well as a measure for nuclear security and non-proliferation (i.e., meeting the "spent fuel standard") involved in this simple process.

TABLE 1. A SIMPLE DRY-PROCESS

Process	Material separated	Material remained	Experience	Meet "Spent fuel standard"[1]?
De-cladding	Metal waste	Spent fuel oxide	PUREX DUPIC[2]	Yes
Voloxidation (Dry process)	Noble gas Volatile fission product (I, Tc)	Uranium TRU Noble metal Rare earth Cs & Sr	DUPIC	Yes
Electro-reduction and uranium separation[3]	Uranium	TRU Noble metal Rare earth Cs & Sr	Pyro-process, by ANL and KAERI	Yes

Notes:
Spent Fuel Standard is defined as the radiation in air from the mid-plane surface of a spent fuel assembly yielding 1 Sv/h at 1 m distance,
DUPIC – Direct Use of PWR spent fuel in Candu,
Further processes to recover TRU (or plutonium) if there is an immediate use of the separated TRU (or Pu).

The disposition of the waste streams of this simple dry-process is shown in Table 2. It indicates that the metal waste from de-cladding can be encapsulated, compacted, and disposed of in shallow land burial. The iodine can be trapped in AgI, immobilized in zeolite, and disposed of in deep boreholes. The technetium can be selectively isolated by a cationic polymeric network [9,10,11], or trapped in calcium filters, compacted, and disposed of in deep boreholes, while noble gases can be bottled and allowed to decay. The separated uranium can be re-used in reactors or disposed of in uranium mines. The remaining materials (TRU, Cs, Sr, noble metals (NM), and rare earths (RE)) would be converted to stable compounds. Protected by radiation from Cs and Sr, the TRU bulk compound would meet the "Spent-fuel Standard". If eventually there is no use for the TRU bulk, it can be "hot-iso-static-pressed (HIP)" into a synthetic rock form (SYNROC) and disposed of in deep boreholes.

TABLE 2. CONTENTS OF SPENT FUEL AND POSSIBLE DISPOSITION METHODS.

Waste Type	Metal waste from de-cladding	Iodine (^{129}I) and technetium (^{99}Tc) from voloxidation	Separated uranium	Remaining material (TRU, Cs, Sr, NM, RE)*
Waste Disposition	Metal waste in containers compacted and disposed of in shallow land burial	• Iodine trapped in AgI & immobilized in zeolite • Tc trapped in Ca filter • These can be compacted and disposed in deep boreholes • Noble gas bottled and decay	Uranium can be used in reactors or dispose of in uranium mines.	• Convert to stable compound and store • Protected by radiation from Cs & Sr • Separated TRU (or Pu) when there is an immediate use • Remaining residue (Cs, Sr, NM, RE etc.) can be HIP into synroc and disposed of in deep boreholes.

* If there is no use for TRU, the remaining material can be hot iso-static pressed (HIP) into synroc and disposed of in deep boreholes

4.2 Deep Borehole Disposal

Deep boreholes represent an alternative method of deep geologic disposal that may offer benefits, particularly for the disposal of certain forms of waste. This concept is less studied than disposal in a mined repository and requires further exploration. The drilling technology for deep borehole concept has now become a more realistic option due to recent advances in commercial and scientific deep drilling technology made in the hydrocarbon and geothermal energy industries. Basically, a deep borehole is a cased hole drilled into crystalline rock to a depth of 4 to 5 km. In most designs, the bottom 1 to 3 km would be filled with vitrified HLW or consolidated spent fuel and some backfill or sealant would be added to fill in the gaps between the wastes and the well casing [12]. Figure 5 shows the schematic of a deep borehole disposal concept.

Deep borehole disposal has the potential to provide very robust waste isolation. The deep borehole disposal concept could significantly reduce the disposal footprint relative to mined repository disposal. The reduction is achieved by concentration of heat in great depth without any surface effects such as subsidence and heat transmission through the host rock. The reduction of disposal footprint could help allay the public concern of “NIMBY” (i.e., not-in-my-back-yard). In addition, deep borehole disposal could achieve a better assurance that the long-lived radionuclide, such as 129I would decay away (after 10 half-lives or 170 million years) during its geologic isolation. It would also make the probability of breaching a borehole by human intrusion unlikely.

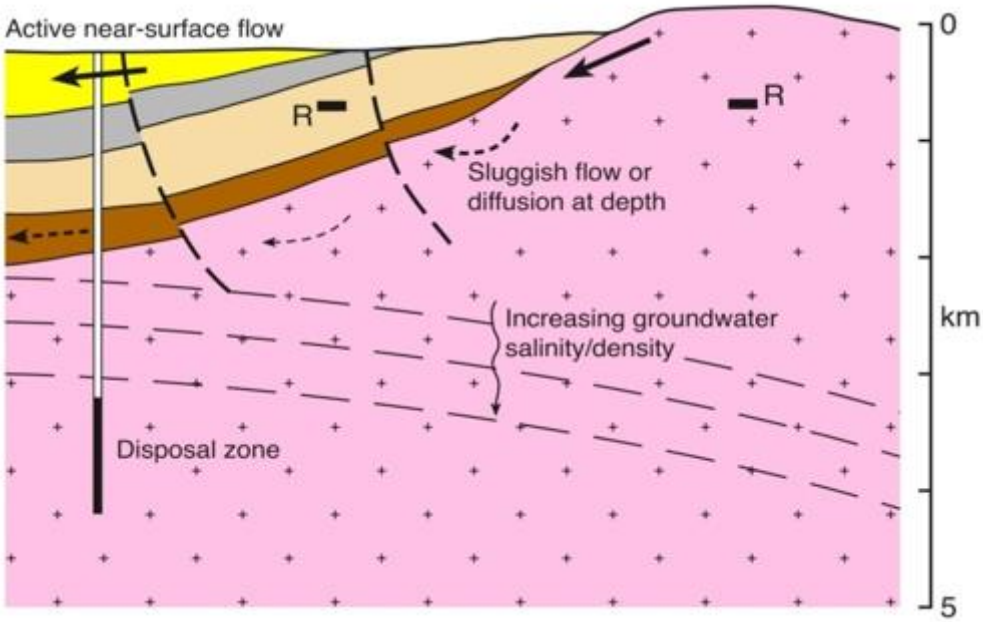

FIG. 5. Schematic of a deep borehole disposal concept (where R is relative depth of a mined repository).

5. CONCLUSION

Future nuclear power expansion requires a resilient fuel cycle which decouples the power generation from long-term spent fuel management, enhances nuclear safety, reduces security and proliferation risks, as well as provide flexibility and retain options for future strategic changes.

A resilient back-end fuel cycle requires innovative technologies, which include novel material for transportation-aging-disposal (TAD) containers; and innovative waste treatment and disposal means. It also requires cooperative institutional frameworks to facilitate spent fuel take-back/away; multi-site/multi-national storage and disposal repository.

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