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Roles and effects of pyroprocessing for spent nuclear fuel management in South Korea

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ABSTRACT

Republic of Korea (ROK) changed its spent nuclear fuel policy from the once-through usage and direct disposal to a total system approach that includes pyroprocessing, sodium-cooled fast reactors, and a two-tier geological repository to achieve a breakthrough for domestic deadlock situation and thus enable sustainable utilization of nuclear power, but caused disagreement in the bilateral negotiation with the United States (US) for the Nuclear Cooperation Agreement.

Analysis has revealed that this shift is effective to make a breakthrough for domestic deadlock because it augments variety of technological options, with which more reversible decision-making process can be conducted to accommodate broad public needs. A trade-off has been explored first by deriving four engineering options from the ROK's system concept and then by comparing their performance from six viewpoints. The option including separation of high-heat emitting radionuclides by the electrolytic reduction process has been recommended.

This option should be modified as exogenous and endogenous situations change in future. It is imperative for ROK to integrate a public-participatory decision-making process that works in concert with technology development. US can verify that ROK's motivation is not deviating from successful spent fuel management by checking if a transparent process with public participation is conducted.

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1. Introduction

Spent fuel management has been a challenge in any nuclear country. Even for countries with advanced technological capability and diverse geological and societal conditions, finding an actual site for a geological repository has proven very difficult politically and societally. Almost all countries that tried to advance from their feasibility study stage to siting stage had a major setback, such as the United States (Blue Ribbon Commission on, January 2012), Canada (Ramana, 2013), and Japan (Ahn and 2013 Oct).

In mid 1980s, Republic of Korea (ROK, South Korea) started its technology development and siting process for interim storage and geological disposal under the scheme of once-through usage and direct disposal (OTDD) because of a constraint imposed by the United States (US) for nonproliferation (see Section 2.3). In the past decade, as its nuclear capacity expanded rapidly, spent fuel accumulation drew public attention. Finding socially agreeable solutions for accumulating spent fuel has been commonly recognized to be crucial for sustainable utilization of nuclear power in ROK, but decision-making process for siting an interim storage facility for

spent fuel has become deadlocked (Ko and Kwon, 2009). With the hope that technological options could make a breakthrough in social decision-making process, despite strong US concern for nonproliferation, in 2008, ROK changed its scheme from OTDD to a total system approach that includes pyroprocessing and sodium-cooled fast reactors (SFR) as core technologies (Long-term plan for promot and 2008 Dec. 22; Park et al., 2009).

Pyroprocessing (Hannum, 1997) proposed by Korea Atomic Energy Research Institute (KAERI) separates elements included in spent fuel into several groups as shown in Fig. 1 by utilizing difference in chemical potentials of constituent elements in high-temperature molten salt. Because of small difference in chemical potentials in such environment, transuranic (TRU) elements¹ tend to be recovered together. This is in principle the basis of ROK's claim that this separation technology is more proliferation-resistant than conventional PUREX process, which was designed for effectively recovering plutonium and uranium.

¹ Actinide includes all the elements of atomic number 89 (Actinium) and above, while transuranic elements (TRU) include Neptunium and above. In uranium-fuel-based reactors, major actinide elements of interest are U, Np, Pu, Am, and Cm. TRU means those without U. "Minor actinide" means TRU without Pu, i.e., Np, Am, and Cm, because of their small masses included in the fuel, compared with Pu mass.

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Fig. 1. Flow diagram of pyroprocessing (RE stands for rare earth elements; GEN-IV SFR stands for a sodium-cooled fast reactor considered in Generation IV reactor development).

Shifting from the OTDD scheme to the total system approach has added the US-ROK bilateral issue on top of all the domestic issues that ROK has to solve for spent fuel management. In addition, because the OTDD scheme is the simplest scheme for spent fuel management, the shift could make the spent fuel management technologically more complicated, uncertain, and costly. Depending on which near-term option is adopted, long-term risk and benefit can be significantly different. While long-term issues such as intergenerational equity and ethics are conceptual, they often become focal points in actual public discussion for siting a geological repository.

Thus, ROK seems to be stepping into a complex, uncertain future by this shift. Is it worthwhile for ROK to make the shift? This question is of universal interest beyond US-ROK bilateral and ROK domestic issues because emerging nuclear countries will eventually experience similar issues in spent fuel management that ROK currently faces, including its relation with US.

In this paper, we compare performance of various technical options derived from the ROK's total system concept for spent fuel management, and recommend a trade-off for ROK's future development and US-ROK negotiation. We first describe brief historical perspective that has resulted in the current deadlocked situation for the spent fuel management in ROK. This is followed by a brief summary on physical aspects of the spent fuel and on the ROK's total system concept. Four technological options are derived from the ROK's system concept, and are compared with respect to multiple viewpoints by using the *scorecard* method (Taebi and Kadak, 2010). Finally, a trade-off option is recommended, which may satisfy various stakeholders.

2. Historical perspective

2.1. Nuclear power utilization

ROK's national plan envisions nuclear power supplying 60% of its electricity needs by 2030 (The first national energy, 2008–2030). This heavy reliance on nuclear power has been motivated by its low self-sufficiency of energy. ROK's self sufficiency is as low as 3%, meaning 97% of primary energy sources, mostly coal, oil,

natural gas, and nuclear, are imported from overseas. The combined share of the indigenous and nuclear power becomes 19%, which is comparable to Japan's 20%,² but far lower than Germany's 40% and France's 51% (Energy balance of OECD countries, 2011).

The reason why nuclear power is often considered together with indigenous sources is because it has characteristics remarkably different from fossil fuels; (1) because of its high energy density, much smaller mass, volume and footprint are required for fuel transportation and stockpiling than those of fossil fuels, (2) geopolitical situations for major suppliers of uranium including Canada and Australia differ from those for oil-exporting countries such as middle-eastern countries, and (3) carbon dioxide emission by nuclear power is remarkably smaller than that by fossil fuel.

By including principally-different energy sources in a portfolio, risks of common-mode failure in importing energy resources have been significantly reduced, and the bargaining power of consumer countries, such as ROK, in the international market of oil and natural gas has been enhanced (Toth and Rogner, 2006), as was observed in the "1980s oil glut" phenomenon (Petroleum Chronology of E and 2002 May). Nuclear power has been contributing to keep the ROK's industry and household electricity prices among the lowest in the world (theoilcrum.com: Discussio and 2010 Dec 11). Thus, for its important contributions to stability of fuel price and supply, and diversity added to the energy portfolio, keeping nuclear power as one of major sources of primary energy has been the ROK's fundamental national energy policy, and is considered to be so in a foreseeable future.

2.2. Spent fuel management under OTDD scheme

With its planned nuclear capacity, ROK is anticipated to generate almost 100,000 metric tons³ of spent fuel by 2100 (Park, 2009). About 1100 tons of spent fuel will be generated annually if and when all planned reactors are constructed. In the meantime, on-site storage at the existing nuclear power plants will reach saturation sometime soon both for CANDU and pressurized-water

² The data before the Fukushima Daiichi accident occurred on March 11, 2011.

³ Same applies throughout this paper.

reactors (PWR) spent fuels (The Organisation for Econ and 2013 Mar 8).⁴

An off-site interim storage facility greatly enhances reliability and safety of the spent fuel management for short- and medium-term spans, until and during disposal of spent fuel into the final geological repository is carried out (The Organisation for Econ, 2006). A geological repository must be prepared as the final reservoir of radioactivity that will not reach a steady state as long as nuclear power is generated, and its hazard potential will last much longer than the use of nuclear energy (Benedict et al., 1981).

The efforts for developing a centralized interim storage for spent fuel in ROK began in 1984. Initially, it was treated as a single siting issue combined with low and intermediate level waste (LILW) disposal. After several unsuccessful attempts of getting public agreement for siting, ROK's Atomic Energy Commission (AEC) changed its policy in 2004, and set the LILW disposal issue apart from the centralized interim storage of spent fuel, which is categorized as high-level wastes (Park et al., 2009). Based on these changes and local citizen voting, a candidate site for LILW disposal was successfully selected in 2005 in the city of Gyeongju, but siting for an interim storage facility remained unsolved.

For the final geological disposal of spent fuel, a study was conducted without specifying a site of a geological repository to explore feasibility of the geological disposal concept in South Korea. Through the 10-year research program between 1997 and 2006, the generic concept for the Korean Reference Spent Fuel Disposal System (KRS) was developed by KAERI for direct disposal of spent fuel from PWR and CANDU reactors (Lee et al., 2007; Hwang et al., 2007). This phase of study is considered to be comparable to similar generic studies in other countries, such as KBS 3 of Sweden (Swedish Nuclear Fuel Supp, 1983), Project Gewähr of Switzerland (Nagra, 1985), and H12 of Japan (Japan Nuclear Cycle Devel, 2000).

Since the middle of 2000s, the most crucial issue in ROK's spent fuel management has been siting of the interim storage, but there was no end in sight to resolving this issue due to lack of public agreement. In such deadlocked situation, the long-term R&D plan (Long-term plan for promoting research and development of future nuclear power system, 2008) was released in December 2008 by ROK's Atomic Energy Commission, as mentioned in Section 1.

2.3. US-ROK bilateral Nuclear Cooperation Agreement

US and ROK have cooperated in the peaceful use of nuclear energy for over 50 years. Since the current bilateral Nuclear Cooperation Agreement (NCA)⁵ was to expire in March 2014, the Obama Administration needed to submit a new agreement, often referred to as a "123 agreement," for the mandatory congressional review period in late spring 2013 for it to take effect before the current NCA expires.

As mentioned in Section 1, on December 22, 2008, ROK's AEC changed its main policy of spent fuel management from the OTDD to the total system by approving Long-term Development Plans for

Future Reactor Systems (Long-term plan for promoting research and development of future nuclear power system, 2008) that included pyroprocessing, sodium-cooled fast reactors (SFR), and very high-temperature reactors (VHTR) as three major pillars in ROK's future nuclear-power system. Because about 60 percent (Squassoni et al., 2010 Jan. 20) of the spent fuel stored in ROK is US-origin, however, the total system approach cannot be achieved without US approval. In official bilateral talks over a new 123 agreement that started in October 2010, South Korea requested that, for its long-term plan to be carried out successfully, it must gain experience working with spent fuel in its own facilities, and that the new agreement should include a provision that would give permission in advance for US-obligated spent nuclear fuel to be treated by pyroprocessing.

The Obama Administration resisted this change, which would pose challenges for US non-proliferation policy based on detailed technical analysis (Wymer et al., 1992 May. 89). Prior to the beginning of this bilateral negotiation, the US DOE's 2008 Draft Nonproliferation Impact Assessment (Office of Nonproliferation and 2008 Dec. 116) concluded that the reprocessing alternatives under discussion, including pyroprocessing, offered only small improvements over PUREX in reducing proliferation risks, primarily affecting the risk that non-state actors would be able to gain access to the plutonium.

This has been one of the key issues in the negotiation of the US-ROK 123 agreement. ROK and US announced on April 24, 2013 a two-year extension of the current agreement (Holt et al., 2013 Jun. 25).⁶

2.4. Why did deadlock occur?

This deadlock seems to have started from failure in developing domestic public consensus. In this sub-section, we consider this question with two key concepts: reversibility and convergence.

2.4.1. Reversibility

The concept of reversibility⁷ has been developed in the international community for years to understand the issue of building public agreement in siting for a geological repository, and is now understood essential for a staged, adaptive approach for spent fuel management (Ramana, 2013; The Organisation for Econ, 2006; Radioactive Waste Managem, 2011; Committee on Principles a, 2003). Because we cannot rely on active management once a repository is finally closed over the many millennia of safety and environmental concern, an adaptive, staged approach should be applied in the storage phase and the pre-closure phase of the final disposal, when the institutional oversight and management capacity to implement responsible course corrections are still available. For a program to be adaptive, the decision-making process must be reversible, supported by flexibility both in technological and institutional systems, because people's values range widely and because program implementation will take at least several generations, during which people's values evolve (Blue Ribbon Commission on, January 2012). Reversibility assures feedback loop in decision-making process, and helps find agreeable near-term options that can achieve long-term performance goal among various options.

Options that can be developed under the OTDD, however, are not so many. Main components in OTDD are interim storage

⁴ For on-site storage of CANDU spent fuels, two kinds of dry storage facilities of 300 concrete silos (with the total storage capacity of 3062 metric tons of uranium) and 7 MACSTOR/KN-400 (M/K-400) concrete storage modules (3175 metric tons of uranium) currently used are expected to saturate by the end of 2018. For PWRs, spent fuels are now stored at nuclear-power plant pools, but all storage pools are expected to reach their full capacity in several years. Storage space at the plant sites was and is being expanded by re-racking and trans-shipment to neighboring plants as a short-term solution until a national spent fuel management policy is determined.

⁵ The current NCA between ROK and US is not based on Article 123 of the Atomic Energy Act since it was concluded before the enactment of the Nuclear Non-Proliferation Act of 1978.

⁶ An extension of the agreement would still require a positive vote of approval by both Houses of Congress in order to come into effect. The two-year extension is considered a temporary solution to avoid any disruption to nuclear trade and provide more time for negotiators.

⁷ The OECD/NEA's International Project on Reversibility and Retrievability defines reversibility as a term that "implies a disposal programme that is implemented in stages and that keeps options open at each stage, and provides the capability to manage the repository with flexibility over time."

facilities and a final geological repository, connected by transportation of spent fuel between such facilities. Packaging and repackaging of spent fuel may be applied for various reasons, such as material degradation and specific requirements of each facility and transportation. Multiple options can still be developed under OTDD basically by changing (1) storage time at and (2) location of each facility, but for a country with small territory, the location factor may not add more options due to limited variety in geological and societal conditions.

If the prefixed option (in the ROK's case, the OTDD) could not get broad public agreement, expanding the public agreement with it furthermore would be difficult. Without good alternatives, adjusting the system to satisfy diverse desire and preference among stakeholders is difficult, and feedback loop in decision-making process would be clogged.

2.4.2. Convergence

Limited public agreement for OTDD could also be explained by considering lack of *convergence*. ROK's long-term energy supply is based on the assumption of sustainable use of nuclear power, as discussed in Section 2.1. Under the OTDD scheme, this implies that the spent fuel stockpile continues to grow, and capacity of interim storage and geological disposal must be expanded accordingly, while it may be possible to slow down the increase of storage space by managing heat emission (Zhou et al., 2010). People could not visualize clearly how sustainable use of nuclear power can be achieved with ever-increasing spent fuel stockpile, and view that situation does not move towards resolution with the OTDD scheme. This would hold better for a country with small territory.

In addition, as repository footprint grows, long-term radiological and proliferation risk of a repository and interim storage would increase, as shown in Appendix A. Thus, the public concern about safety of ever-expanding capacity in the OTDD scheme is not just conceptual, but substantive.

Successful interim storage operation and nomination of Östhammar in 2009 as the site for the final geological repository in Sweden should be touched upon here in the context of convergence. On March 23, 1980, following the results of the referendum, the Riksdag, the Swedish Parliament, decided that no further nuclear power plants should be built and that a nuclear power phase-out should be completed by 2010. By this decision, the amount of spent fuel that the Swedish spent-fuel management system based on OTDD had to deal with was fixed. Success in Sweden gives circumstantial evidence for the aforementioned observation that the convergence in the scale of spent fuel accumulation could be crucial for development of public confidence.⁸

3. Characteristics of spent fuel and ROK's total system concept

In this section, to prepare for the subsequent discussions on pyroprocessing, we observe general characteristics of spent fuel by considering two distinct groups of radionuclides contained in spent fuel (Table 1): (Forsberg and 2000 Aug),⁹ High-Heat

Radionuclides (HHR) (Sr-90 and Cs-137) with short half-lives (about 30 years) and small masses (approximately 4 kg/metric ton of initial heavy metal (MTIHM)); and Low-Heat Radionuclides (LHR) with long half-lives and significant masses. In Section 3.3, we observe the ROK's two-tier repository concept accommodating them separately.

3.1. High-Heat Radionuclides

While nuclear power generation by the fleet of reactors in a country is kept constant, the cumulative radioactivity of HHR will increase, but because HHR also decays with the half-life of 30 years, asymptotically approach a certain upper bound. This upper bound is determined by the size of the fleet, but not by duration of time of the fleet operation, as Eq. (B.8) in Appendix B shows that non-dimensionalized parameter k , which represents the total fleet size at the equilibrium stage normalized by a unit reactor size, determines the magnitude of accumulated mass of HHR. Thus, if HHR is separated from LHR, convergence is achieved for interim storage and final disposal of HHR. As Appendix A explains, separation of HHR reduces the total repository footprint substantially, which improves the radiological performance of the repository substantively.

At the end of the nuclear phase-out era, when nuclear power capacity becomes zero, there always remains HHR waste that requires confinement beyond the phase-out era. Because it also includes the long-lived Cs-135 (half life of 2.3 million years), remaining HHR must be transferred to the LHR repository. Within 100 years after the phase-out, heat emission from the remaining HHR becomes sufficiently low, so that it can be transferred to the LHR repository.

3.2. Low-Heat Radionuclides

As Table 1 shows, LHR includes uranium isotopes, plutonium and minor actinide isotopes, and long-lived fission products (LLFP), such as I-129, Se-79, and Tc-99. In addition, Cs-135 would be added to this group after HHR has cooled down, as discussed in Section 3.1.

Uranium isotopes occupy ~95% of the mass of spent fuel from a typical commercial light water reactor. About 1.5% is U-235, which is fissile, and the rest is mostly U-238 with small fractions of U-236 and 234. Half-lives of these U isotopes range from 240,000 years (U-234) to 4.5 billion years (U-238). Uranium is chemically a redox-sensitive element, and is hardly soluble in groundwater and strongly sorbing on rock minerals in a reducing environment.

Plutonium and minor actinides, or transuranic elements (TRU), emit heat, not as much as HHR, but substantially more than LLFP and U. Because these isotopes are fissionable, stringent control for safeguards and safety is required. They are also highly radiotoxic due to alpha-particle emission. These elements are redox-sensitive, and hardly soluble in groundwater and strongly sorbing on rock minerals in a reducing environment.

Long-lived fission products (LLFP) are relatively mobile in geological formations, because of high solubility and weak sorption with rock during hydrological transport by groundwater.

After the LHR-HHR separation, these three sub-groups (U, TRU, and LLFP) in LHR still exist as one bulk solid phase. Because of substantial difference in materials properties, further separation of these three groups and sequestration with suitable waste forms tailored for individual separated materials can be considered (Committee on Waste Forms, 2011). For TRU, transmutation can also be an option, which converts them to less toxic, un-fissionable isotopes by fissioning them in a nuclear reactor or an accelerator-driven system. In any of those conceivable options, the geological repository is necessary (Committee on Separations, 1996) because

⁸ In June 2010, Riksdag voted to repeal the phase-out policy, and allowed replacement of existing reactors. It is interesting to see how this decision affects the future steps in development of the geological repository in Sweden.

⁹ There has been a historical assumption that high-level waste (HLW) contains both in a single waste form. For example, if spent fuel is regarded as HLW, spent fuel that contains both LHR and HHR is treated as a single waste form. Vitrified HLW resulting from the conventional PUREX reprocessing contains both LHR and HHR; because the primary objective for the PUREX reprocessing is to recover plutonium and uranium, the remainder including Sr, Cs, minor actinides, and other fission products is solidified in a single waste form.

Table 1

Decay heat (watts) from one metric ton of PWR spent nuclear fuel with burnup of 40,000 Mega watt day per metric ton of initial heavy metal (Forsberg and 2000 Aug).

Time, years	Spent fuel	HHRs (Cs and Sr)	LHRs			Structure
			U and Pu	Minor actinides	Other FPs	
10	1443	1024	185	113	64	48
20	1096	755	211	90	22	13
50	658	373	228	55	2	0.3
100	356	115	201	39	0.1	0.05
1000	63	~0	54	9	0.02	0.02

Note: Structural materials include the claddings, assembly materials, crud and other activated materials by neutron irradiation in a reactor. Because they can be easily separated from other portions of LHR at the stage of separation between HHR and LHR, they are not included in the LHR in the discussions hereafter, unless otherwise specified. HHR also includes other isotopes of Cs and Sr than Cs-137 and Sr-90, if recovery of HHRs from spent fuel is done by a chemical separation method. Considering their half-lives, the only remaining isotope other than Cs-137 and Sr-90 is Cs-135 with the half-life of 2.3 million years. Its radioactivity is about million times smaller than that of Cs-137 at the time of discharge from a nuclear reactor, and has negligible contribution to heat emission. But, because of its longevity, HHR still needs to be treated as radioactive waste after the two major isotopes, Cs-137 and Sr-90, have decayed out. See the main text.

there still remain isotopes with half-lives much longer than the time span of nuclear utilization. Thus, multiple technological options can be considered for LHR as discussed in Section 4.1.

3.3. ROK's total system concept

The KAERI's concept includes separation between HHR and LHR, further separation of LHR, transmutation of TRU by SFR, and the concept of a two-tier geological repository, A-KRS, for wastes from HHR and LHR (Yoon et al., 2010) (Fig. 2). In relation with the aforementioned general observation on HHR and LHR, the following is observed:

- The separation of HHR and LHR is achieved by the processes up to the end of the electrolytic reduction stage (to the left of the vertical dashed line in Fig. 1), generating HHR (Cs and Sr), off-gas, and the structural materials hull. Among the LLFP in LHR, volatile/gaseous FPs are separated and collected by the off-gas treatment system prior to the electrolytic reduction.
- The HHR waste is to be placed in the upper tier (at depth of 200 m) of the A-KRS repository. After cooling, it can be transferred to the lower tier (500 m), if necessary. This 200-m level space functions mainly as a storage space, and can also be used as a final disposal space for structural materials wastes.
- After U and TRU are recovered from LHR by the electro-refining and electro-winning processes, respectively, remaining low-heat-emitting HLW will be solidified. This HLW, containing fission products (excluding HHR and gaseous/volatile isotopes) and trace amount of U and TRU, will be placed in the lower tier (500 m) of the repository immediately because no cooling is necessary.
- TRU mixture and part of U are used to manufacture SFR fuel in a metallic form.
- Remaining U is stored for future use as the SFR fuel, or disposed of in the repository.
- Iodine-129 included in the off-gas trapping is to be stabilized with an appropriate robust solid matrix for final disposal at the 500 m level.

4. Multifaceted performance assessment

In this section, we derive three options for treatment of LHR based on the KAERI's total system concept, and compare them with the OTDD as the reference option.

4.1. Options for comparison

We compare the following four options:

- Option (0): OTDD. This option includes relocation and/or repackaging of spent fuel.
- Option (I): The electrolytic reduction process separates HHR and LHR. No further separation for LHR is applied. HHR is stored at the storage space at the 200-m depth, and then transferred to the 500-m depth space after some cooling time (~100 years). LHR is immediately disposed of in the repository at the 500-m depth. For interim storage of spent fuel before the LHR-HHR separation, the same interim storage in Option (0) may be included in this option, or alternatively, the 200-m depth space can be used with additional ventilation capability.
- Option (II): After separation of HHR from LHR by the electrolytic reduction, separation of LHR into U, TRU/U,¹⁰ and LLFP is made by electro-refining and electro-winning. Separated materials are conditioned into respective waste forms with high robustness. TRU transmutation by SFR is not included in this option. The rest is the same as Option (I).
- Option (III): This is the same as the KAERI's concept. After separation of HHR from LHR by the electrolytic reduction, separation of LHR into U, TRU/U, and LLFP by electro-refining and electro-winning is made. Separated TRU/U is manufactured into metal fuel for SFR by adding U and Zr, and transmuted by SFR. Spent SFR fuel is processed by the electro-refining and electro-winning processes, and recycled as metal fuel to SFR.

4.2. Viewpoints for multifaceted assessment

Performance of these options is compared from multiple viewpoints. There can be a large number of viewpoints, particularly for complicated issues, because different stakeholders would consider different sets of viewpoints more important than others. Viewpoints for assessment should be selected to reflect representative values shared in the society. Therefore, to select a set of viewpoints for a multifaceted assessment, a discussion participated by various stakeholders should be conducted. We will revisit the public participation feature in this assessment approach in Section 5.4.

In this paper, instead of conducting public-participatory discussions, a set of viewpoints has been selected, based on discussions extended in Section 2, in which couplings between international/bilateral and domestic issues and between short-term and long-term issues have been observed. In Fig. 3, these couplings are expressed as two axes. On the two-dimensional space, six viewpoints are located. Three on the left side are related to domestic matters: radiological safety for geological disposal, radiological safety for fuel-cycle activities prior to geological disposal, and development of decision-making for siting. Three on the right side are related to international matters: proliferation resistance of geological disposal, proliferation resistance of fuel-cycle activities prior to geological disposal, and US-ROK bilateral relations.

While cost is important, it is not included in the present comparison partly because of uncertainty in cost evaluations (Kim et al., 2013). More importantly, in social decision making, the primary and most fundamental part of discussions should focus on (1) recognition of problems and difficulties that the society is currently facing or is anticipated to face in future, and then on (2) visualization of a "goal," i.e., situation in which those problems/difficulties are considered to be settled. Once the public could share this fundamental problem

¹⁰ This "TRU/U" product after electro-winning still contains U with the ratio of about 25% (U) to 75% (TRU).

Fig. 2. Conceptual diagram for A-KRS repository.

framing and reach a consensus about what the society would like to achieve, in the next round of discussion, cost of available options would become the most important issue for selection. It should be noted that even if a certain option is found to be overly expensive, it can often be overcome by technological development and breakthrough, if there is a strong societal motivation toward it. A good example is the Muskie Act of 1970 for air quality control, which accelerated technological development of automobiles with much less air pollutant emission. One of major reasons for the current deadlocked situation in ROK's spent fuel management is lack of fundamental problem framing and consensus about what the society would like to achieve. The present paper focuses on an analysis that would help the first-round discussion.

The four options explained in Section 4.1 are ranked with respect to each viewpoint, based on results of previous quantitative studies as well as qualitative judgments. We apply a disaggregate approach, which separately presents various performance aspects for each option. The approach uses a method introduced by policy

analysts to compare policy alternatives, which is also known as the *scorecard* method (Taebi and Kadak, 2010). The scorecard can assist us to clarify trade-off relations among options.

4.3. Results of assessment

Table 2 summarizes the results of the assessment. Detailed discussions that have led to the ranking for each viewpoint follow.

Table 2
Scorecard for options of spent fuel management.

Viewpoints	Determining factors	Options			
		(0)	(I)	(II)	(III)
(a) Radiological safety of a geological repository	Mass release rates of radionuclides from the repository	4	3	2	1
	Option (II) with VHTR	4	3	1	1
(b) Radiological safety of processes in the fuel cycle	Complexity and amount of work included in respective options	1	2	3	4
(c) Decision-making for siting	Variety of options available for decision making	4	3	2	1
(d) Proliferation resistance of a geological repository	Attractiveness of the wastes to be placed in a repository	2	3	4	1
	Option (II) with deep bore-hole disposal	3	4	2	1
	Option (II) with VHTR	3	4	2	1
(e) Proliferation resistance of processes in the fuel cycle	Likelihood of generating stockpile of weapons-usable materials	1	2	3	4
	Option (II) with VHTR	1	4	2	2
(f) US-ROK bilateral relations	Sensitiveness of processes and technologies	1	2	3	4

Option (0): Once-through and direct disposal of spent nuclear fuel in a single mined repository.

Option (I): Separation of HHR from LHR by the electrolytic reduction. HHR is stored at the upper tier in the A-KRS repository, while LHR is at the lower tier.

Option (II): In addition to Option (I), LHR is further separated by electro-refining and electro-winning into U, TRU and Long-lived fission products, each of which is conditioned into suitable waste form for disposal and disposed of at the lower tier of the A-KRS repository.

Option (III): After separation, U and TRU are made into metal fuel for SFR. Spent SFR fuel is treated by electro-refining and winning for further recycling.

Legend: 1: best; 2: second; 3: third; 4: worst.

Fig. 3. Viewpoints selected for the present multifaceted assessment.

Note that this ranking is not in the same scale across the viewpoints. For Viewpoints (a), (d) and (e), rankings for the cases with supplemental technologies are also shown. Discussions for these are given in Sections 5.2 and 5.3. Fig. 4 shows those results in the radar-chart format, in which viewpoints are located at corresponding locations in the two-dimensional space shown in Fig. 3.

4.3.1. Radiological safety of a geological repository

Long-term radiological safety of a geological repository is quantitatively assessed and regulated in terms of the annual dose to the public. As far as the repository of each option meets regulatory requirements for maximum allowable dose, there should be negligible difference among the options compared. Under normal conditions, due to low solubilities and strong sorption onto rock minerals, TRU isotopes would be unlikely to reach the human environment over the millennia, and so radiological impacts can be made sufficiently small. The long-term radiological risk of the repository is, therefore, determined by the behavior of LLFP such as I-129, Cs-135, and Tc-99, which are mobile in geological formations.

What we actually compare for this viewpoint is difficulty for meeting regulatory requirements on radiological risk. We consider that this would be approximately proportional to the magnitude of the source term. The source term is physically represented by the total mass release rate of radionuclides from the repository. For radionuclides with low solubilities, such as actinides, the release rates are proportional to the total surface area of waste packages exposed

to groundwater flow (Ahn, 2008). For radionuclides with high solubilities, such as FP, the release rates are determined by the robustness of the waste form, i.e., the dissolution rate of the waste form.

In Option (0), fractions of I-129 and other volatile FP exist in the gaps between fuel cladding and pellets in spent fuel, and will be released early and fast, when packages fail in the repository, which conforms a prominent peak in the annual dose curve (Yoon et al., 2010 Feb). In Options (I) (II) and (III), by the HHR-LHR separation, I-129 is collected in the off-gas stream, for which a robust waste form can be tailored for sequestration. This makes Option (0) worse than the others.

In Option (I), separated LHR is treated together. From one metric ton of LHR, about 300 to 200 W of heat is emitted during the first 100 years (Table 1), which requires a smaller number of packages than that for spent fuel (Option (0)) by a factor of 2.5 (Forsberg and 2000 Aug) to 6 (Kawata and 2007 Dec), resulting in smaller mass release rates from the entire repository for Option (I) than for Option (0).

Because heat-emitting TRU is separated from LHR in Option (II), disposal of U can be done, as suggested in Forsberg (2000), with a large silo type repository, similar to the Swedish LILW Repository (The Swedish Nuclear Fuel and 2010 Apr 9). Thus, Option (II) is expected to give smaller total release rates than Option (I).

For Option (III), comparison would be more complicated than comparison among Options (0), (I) and (II) because by burning TRU in SFR, additional electricity and spent SFR fuel are generated. While space for TRU disposal is eliminated, space for HHR and LLFP

Fig. 4. Comparison of options by performance. Solid lines: No supplemental addition; Broken lines: Option (II) with deep bore-hole disposal; Dashed lines: Option (II) with VHTR.

that are generated by burning TRU in SFR must be added. To be fair with the other options, comparison should be made on the same electricity generation basis. Because FP generation is roughly proportional to the amount of electricity generated by fission, if we normalize by electricity generation, contribution by HHR and LLFP is approximately unchanged.

4.3.2. Radiological safety of processes in the fuel cycle

The activities in the fuel cycle include interim storage, transportation, pre-closure repository for Option (0), and, in addition to these, respective separation processes for Options (I) and (II), fuel-making process, and SFR operation for Option (III) are included. Under normal operation condition, actual risk to be imposed on the public and the worker is subject to strict regulation. What is compared from this viewpoint is complexity of processes and activities included in respective options, and so amount of regulatory work necessary to maintain normal operation.

In Option (0), spent fuel is encapsulated in cladding, assembly casing, and metal cask. Additional overpack may be added as the outermost package for disposal. Thus, efforts for achieving the radiological safety for the public and the worker set by the regulation guidelines would be the smallest. Those for Options (I), (II), and (III) increase in this order because they include increasingly more facilities and processes, such as segmenting irradiated fuels, separating HHR from LHR, and conditioning separated materials into stable forms.

4.3.3. Contribution to decision-making for siting

From the discussions in Section 2.4, it has been recognized that variety of options and convergence in waste accumulation are imperative for developing societal agreement, and OTDD is inherently difficult in these two attributes. Thus, Option (0) is ranked the worst among the four options.

In terms of the variety, Options (III) would be the best, while Option (II) the second, and (I) the third, dependent on the level of separations of materials. In terms of convergence, the physical repository footprint would be reduced in the order of Options (I), (II), and (III).

4.3.4. Proliferation resistance of a geological repository

For this viewpoint, we compare attractiveness as weapons-usable materials. It is assessed by the mass of TRU contained in the waste and to the level of radiation emitted from the waste.

The waste placed in the repository in Option (III) contains trace amount of TRU. Thus, the proliferation risk would be significantly smaller than the other options. Dependent on the level of burn-up by SFR, safeguards inspection for the geological disposal may be terminated (Department of Safeguards, 1990 Mar). The mass of TRU and U to be placed in the respective repository in Options (0), (I), and (II) is the same, but the forms of materials are substantially different, resulting in different proliferation risk. Option (0) is considered the lowest among these three because of high radiation barrier especially in the pre-closure stage (Appendix A). Option (I) is better than Option (II) because TRU is mixed with the large mass of U. Option (II) is the worst because TRU is separated and stored in a compact form, which would make diversion easier than in other options.

4.3.5. Proliferation resistance of processes in the fuel cycle

Proliferation risk for fuel-cycle activities can be measured by various ways. One way is to quantify the probabilities of false alarms (Type I) and material diversion (Type II) (Khalil et al., 2009; The Proliferation Resista and 2011 Sep 15). For this approach, detailed process design and inspection procedures must be known, neither of which is currently available. In this section, we focus on likelihood of generating stockpile of weapons-usable materials from fuel cycle processes included in each option and accountancy for such materials.

In Option (0), TRU and U are encapsulated in fuel pins and assemblies protected by high radiation. In Option (I), TRU is still included in the bulk U, which would make TRU less attractive than that generated in Options (II) and (III), in which TRU exists together with small amount of U after the electro-winning stage (see footnote j). Based on this observation, Option (0) is ranked the best for proliferation resistance of the fuel cycle activities. Among Options (I), (II), and (III), Option (I) would be ranked better than Options (II) and (III). Comparison between Option (II) and (III) is more complicated. Separated TRU/U or U needs to be tailored to appropriate forms in either option. In Option (II), TRU/U needs to be solidified for disposal. In Option (III), it needs to be manufactured into SFR fuel. In terms of material accountancy, these require similar level of efforts for safeguards. In Option (III), while TRU/U is transmuted by SFR, there is a concern that mismatch between production and consumption of TRU/U metal fuel occurs. Because of this point, Option (III) is ranked the worst in the present comparison.

4.3.6. US-ROK bilateral relations

As described in Section 2.3, preventing proliferation of sensitive nuclear technologies and materials is the US policy. It is clear that Option (0) is the best match for US policy. Option (III) is ranked the worst not only because it includes sensitive technologies that enable separation of weapons-usable materials, but also because it includes SFR. As the previous study (Wymer et al., 1992 May. 89) points out, if the rationale for the SFR as a burner is given great weight in the waste management, it might serve to stimulate interest in reprocessing (including in aqueous systems) in countries that obviously face waste management problems, and the US would prefer to see remain on a once-through fuel cycle for reasons of nonproliferation.

Option (II) includes electro-refining and winning processes, which US regards de facto reprocessing by the 2008 assessment (Office of Nonproliferation and 2008 Dec. 116) as discussed in Section 2.3. The fundamental technologies for these processes were developed and demonstrated by Argonne National Laboratory and Idaho National Laboratory for the metal fuel recycle for SFR.

Option (I) includes the electrolytic reduction. This is the key technology that connects the oxide fuel used in LWR and CANDU with the subsequent metal fuel cycle for SFR, and still needs substantial technological breakthrough. It would be beneficial also for US if this technology is put into practical use. As discussed in Section 3, separation between HHR and LHR is in general effective to provide more options for spent fuel management and to improve performance of geological disposal. Although there is no concrete plan for applying this option in the current US spent fuel management program, realization of electrolytic reduction may have beneficial impacts also on the US program. Considering that close collaboration between ROK and US for pyroprocessing including electrolytic reduction has been carried out (See Section 2.3), technological breakthrough with electrolytic reduction would make positive influence on the bilateral relation.

5. Discussions

5.1. Trade-off options

Observing Table 2 and Fig. 4, we notice that the disagreement between US and ROK described in Section 2.3 resulted from the conflict of their priorities between long-term (Viewpoints (b)(e)(f)) and short-term matters (Viewpoints (a)(c)). US seems to consider minimization of short-term risks the most crucial, while ROK aims at maximization of long-term performance. Option (0) achieves safety and safeguards in the short and medium terms, while Option (III) achieves higher level of safety and safeguards in the final repository and sustainable nuclear-power utilization. Option (0) does not cause

any difficulty in US–ROK bilateral relation, but public decision-making in ROK has experienced difficulty with Option (0) because of limited variety of options, while Option (III) is exactly the opposite.

As summarized in Section 2.1, ROK's ultimate goal is to achieve prosperity of its economy based on stable supply of primary energy, while US goal is to achieve safety and safeguards in international community by avoiding proliferation of sensitive nuclear technologies and materials. These goals are not isolated or conflicting each other, however. ROK's prosperity is more likely to be achieved in a stable, safeguarded world. US policy is based on the assumption that safeguardability and safety of nuclear power utilization by non-weapons countries would be maximized under the OTDD scheme. While this may be the case under the situation in near/medium terms, as stockpile of spent fuel increases in those countries, the OTDD may not be the solution that always works. Actually, also in US, the Blue Ribbon Commission recommended to continue to search for alternative options (Blue Ribbon Commission on, January 2012). This interdependence of respective motives and goals implies a possibility of finding trade-off options.

Option (I) shows well-rounded performance in all viewpoints. It can bring in convergence feature into the capacity of storage and final disposal, so that the public decision-making process can have effective feedback loops to find an agreeable solution. It can also improve the radiological safety of the repository. For the US concern about nonproliferation, TRU is not separated from the bulk mass of U and is still contaminated with LLFP. Further separation is necessary for generating weapons-usable materials, implying sufficiently far from actual weapons production. Unlike the electro-refining and electro-winning processes, which were demonstrated and owned by US national laboratories, the electrolytic reduction still requires major technical breakthrough. If it is achieved, Option (I) can be mutually beneficial.

Option (II) lacks proliferation resistance both in the repository and the fuel cycle, because the TRU/U stockpile is generated in this option. The stockpile issue can occur in any fuel cycle option, and once it happens it can cause international concerns, as the recent Japanese plutonium stockpile issue indicates (US–Japan Nuclear Working Group, 2013). Thus, for this option to be a trade-off option, some supplemental technologies that reduce the concern of TRU stockpile must be made available in a timely manner. In the next sections, we consider such technological supplements.

Option (III) would be unlikely to realize at least in near future, mainly because it conflicts with the US nonproliferation policy and because of immaturity of necessary technologies, while it has superior performance in long-term radiological safety and proliferation resistance with geological disposal. However, if we consider Options (I) to (III) as different stages of evolution, Option (III) could be a reasonable option that comes after Option (I) or Option (II) is realized.

5.2. Very high temperature reactor

The very high-temperature reactor (VHTR) is one of the three main components of the Long-term Development Plans for Future Reactor Systems approved by Atomic Energy Commission (Long-term plan for promot and 2008 Dec. 22). VHTR has been known for its high reliability and safety (Weinberg et al., 1984 Jan 29; Hart and 2010 Sep. 131; Nishihara et al., 2006), low capital, maintenance and operational costs (Gandrik and 2012 Jan.; Takei et al., 2006), high burn-up, and production of high-temperature gas, which can be used for various purposes, including production of hydrogen and steel. Actually, the main role of VHTR in the ROK's long-term plan is production of high-temperature gas for chemical processing, particularly hydrogen production.

It uses TRISO particles (Nickel et al., 2002) as fuels. In addition to the aforementioned advantages, VHTR with TRISO fuels can burn Pu-239

very effectively (Greenspan et al., 2006). More than 95% of Pu-239 can be fissioned by one irradiation cycle. The resultant spent TRISO fuel, which is usually embedded in graphite matrix, has found to be very robust in any geological environment, yielding significantly lower long-term radiological risk of geological disposal than LWR spent fuel (van den Akker et al., 2013 Mar). Because of deep burn of Pu in VHTR, safeguards inspection may be terminated for geological disposal of spent TRISO fuel. Therefore, if we use the VHTR as an effective Pu burner, it could reduce concern for stockpile of separated TRU in Options (II) and (III). This consideration would change the ranking for viewpoints (a) (d) and (e) as shown in Table 2 and Fig. 4. The results show that by adding VHTR, Option (II) becomes very attractive.

5.3. Deep bore-hole disposal

Application of deep bore-hole disposal (Brady et al., 2009 Aug. 75) would reduce some of the risks observed in Section 4.3 significantly. First, the long-term radiological risk resulting from iodine can be reduced significantly in Options (I), (II), and (III). Because I-129 is weakly sorbing, highly soluble in groundwater and very long-lived (half-life of 17 million years), it has been considered difficult to sequester in the geological environment until it decays out. Recently, a possibility of preventing it from appearing in the biosphere has been pointed out, if it is disposed of at sufficient depth (Orucoglu et al., 2013).

Second, long-term radiological and proliferation risks associated with TRU particularly in Option (II) can be significantly reduced by deep bore-hole disposal. If a deep bore-hole disposal is applied for TRU for Option (II), retrievability of TRU can be made very small, and the risk of proliferation could be closer than the original Option (II) to Option (III); the ranking for Option (II) with respect to viewpoint (d) would be changed as shown in Table 2 and Fig. 4.¹¹ Even in this case, there would be a time between the separation and disposal when separated TRU exists as stockpile, but this could be an interesting alternative to transmutation by SFR. Potential issues would be epistemic uncertainty associated with geological phenomena and concern for criticality events in deep underground.¹² Because of very limited retrievability, these should be carefully examined.

5.4. Public-participatory discussions

Because the ROK's shift from OTDD to the systems approach was motivated by the difficulty in developing broader public agreement, the multifaceted assessment should also be conducted in staged, adaptive manner with public participation, and accordingly the technology development should be guided by public-participatory process of decision-making.

¹¹ In the present study, these supplements (VHTR and deep bore-hole disposal) are considered only with Option (II). For the case of Option (II) supplemented with deep bore-hole disposal, some of those separated materials are assumed to be disposed of in deep bore-holes. This changes rankings of Option (II) with respect to six viewpoints, and accordingly rankings of options (0), (I), and (III) do. In the diagram of Option (0), the ranking of this option for repository proliferation resistance is down-rated from the second to the third, because Option (II) with deep bore-hole disposal was ranked up to the second. The ranking of radiological safety of repository for Option (0) does not change even if Option (II) is supplemented with deep bore-holes, because Option (0) is ranked the worst due to the contribution by early release of iodine in the gap between the fuel cladding and the pellets.

¹² We can reasonably guess that there would be negligible impacts on the human environment on the surface, but we cannot exclude scenarios in which criticality events would cause massive fracturing of host rock, alter groundwater flow, and radionuclides reach the biosphere. Basically, this is a concern for "unknown unknowns," and if something catastrophic happens, there are very limited options available for mitigation.

In this study, the six viewpoints have been selected and ranking among four options for each viewpoint have been determined by the author's analysis and judgment, based on various related studies previously reported. No matter how carefully this is done, the present result reflects the author's value and interest. The present approach, however, indicates a good potentiality to implement public participation, and help reversibility of the decision-making process because of the following two points.

The first point is about the selection of viewpoints for multifaceted assessment. Different stakeholders would have different priorities, and thus consider different sets of viewpoints more important or crucial. However, including too many viewpoints would not make assessment useful for grasping trade-off relations embedded in the current issue. This leads to an idea of establishing a public committee with participation of various stakeholders for the purpose of selecting a relatively small number of viewpoints for multifaceted assessment.

The second point is about evaluation/ranking for each viewpoint. While historically this has been done based on judgment of technical experts as shown in this paper, the public should also be given an opportunity to participate in evaluation. Multiple sets of results for different population could be obtained and compared, which will be useful for understanding difference in preference among stakeholders.

6. Concluding remarks

The KAERI's total system concept has a potentiality of generating a variety of engineering options for spent fuel management, which result in different combinations of cost, risk, and benefits. The public and policy makers can choose one from these options, and use these as the basis for developing more agreeable options. This is also expected to help development of agreement in the US-ROK bilateral negotiation.

Some of those options have been discussed in this paper. Among those, Option (I) presently seems to be a reasonable trade-off for both US and ROK. For ROK, Option (I) satisfies a prerequisite of the spent fuel management including separation, and enables more flexible repository management, reduction of repository footprint, and improvement of repository performance. While it might seem to close the path to their desired SFR, future extension of the system is still possible. For US, this is recession from the ideal state, i.e., OTDD, but majority of the material included in spent fuel still remains as bulk LHR material without separation of TRU. Option (I) is also helpful to develop technological diversity and breakthrough in spent fuel management.

Option (II) is likely to cause US concerns about generation of stockpile including TRU. If it is supplemented by VHTR and/or deep bore-hole disposal, this option can also become more agreeable. Because neither VHTR, deep bore-hole disposal, nor electro-refining/winning is fully matured technology, it will take substantial time for this option to become actually available.

The exogenous and endogenous situations in and around ROK will evolve with time. Accordingly, a choice can also evolve with situations. Thus, it is recommended to consider Option (I) as the near-term option that is likely to be agreed by both US and ROK, and depending on evolution of external situations and technological development, Options (II) and (III) can be considered as future upgrade options. This may seem to be the same as the current ROK's long-term plan, which aims at Option (III) directly. But, it should be noted that the staged approach recommended in this paper is substantially different from the current ROK's plan, in that it can be more responsive to change, and that it provides

more opportunity for people to participate in decision-making process.

Developing pyroprocessing capability is effective for enhancing resilience (Hollnagel et al., 2006) of ROK's nuclear power utilization, because it provides flexibility to cope with such evolution and change. For US, this may seem to be an endorsement for its concern that even a small concession might eventually stimulate interest in full-scale Pu utilization in ROK that the US would prefer to see remain on OTDD for reasons of nonproliferation.

If we remember that pyroprocessing and related technologies are sought by ROK because of difficulty in developing public agreement for OTDD as discussed in Section 2, US can verify that ROK's motivation is not deviating from successful spent fuel management by checking if transparent decision-making process with public participation is conducted in ROK. It is imperative for ROK to integrate a public-participatory decision-making process that works in concert with technology development. Technological and societal hurdle for ROK may be higher for this path than for OTDD, but this is a responsible innovation worthwhile for both ROK and US to try to achieve a breakthrough for innovative spent fuel management.

Appendix A. Effects of HHR-LHR Separation

A.1. Effects on Repository Footprint

A footprint per canister multiplied by the number of canisters determines total repository footprint. The footprint per canister is determined in such a way to assure the temperature around a canister is always below a certain temperature because durability of a waste package is better at lower temperature in and around the waste container. To make sure the temperature is always below a certain level, waste containers are placed in host geological formation with a certain pitch distance to dissipate heat. With a greater number of waste canisters, the total mass release rate of radionuclides from failed canisters in the repository becomes greater (Ahn et al., 2002; Ahn, 2004).

While various previous studies (Ko and Kwon, 2009; Forsberg and 2000 Aug; Kawata and 2007 Dec; Wigeland et al., 2006 Apr) show that HHR-LHR separation would reduce the footprint, others claim that, if spent fuel is stored until it cools down to the same level of heat emission as the LHRs, footprint can be reduced without separation (von Hippel and 2010 Mar).

Suppose spent fuel is stored for cooling for 300 years to make its heat emission as low as that of the LHR. Because of the concern of materials degradation by elevated temperature, at the end of, or even within, the storage time, repackaging would be required. This raises issues associated with materials handling and accounting, such as cost and proliferation concerns. These may still be manageable as long as nuclear power utilization continues, because the cost could be internalized while selling nuclear electricity generates the revenue. However, after nuclear utilization is phased out, they would become significantly more difficult for OTDD because of lack of revenue and large mass of spent fuel. To reduce the repository space to the same level as that for the LHR disposal, the interim storage for 300 years would be necessary, which would be burden on the future generations beyond the nuclear phase-out. If spent fuel is placed in a geological repository while it is still hot to avoid burden on the future generation, the repository footprint would not be reduced.

Contrary to OTDD, if the separation is applied at the early stage of the spent fuel management, the mass of HHRs is significantly smaller (~4 kg as opposed to 1 metric ton of spent fuel), and packaging for HHR would be less expensive and more reliable.

Because of low heat emission from LHRs, LHRs can be contained in a small number of large-volume containers with smaller pitch distance between containers. Therefore, the repository footprint requirement for LHRs would be small right after separation between LHRs and HHRs; no interim storage for the cooling purpose is necessary. Thus, separation between HHRs and LHRs can significantly reduce the need for storage beyond the phase-out era, and would make reduction of repository footprint more realizable.

A.2. Effects on Proliferation Resistance

The second point is about proliferation resistance of the LHRs. Figure A.1 illustrates the dose in the vicinity of a spent fuel package designed for Yucca Mountain Repository. It indicates that after cooling for 100 years the dose received by a person standing for 8 h at 1 m from the spent fuel package will be only 10 mSv, which is not lethal at all. The gamma dose is mainly from HHRs while the neutron dose is due to the TRU isotopes. This implies that the packaged LHRs would not have safeguards protection by radiation.

Because of this ever-decreasing protection by radiation and inclusion of fissile and fertile isotopes, IAEA will not terminate safeguards on spent fuel in a geological repository even after the final closure (Department of Safeguards, and 1988 Dec. 70). IAEA recommended the adoption of the following policy statement: “Spent fuel disposed in geological repositories is subject to safeguards in accordance with the applicable safeguards agreement. Safeguards for such material are maintained after the repository has been back-filled and sealed, and for as long as the safeguards agreement remains in force.” For example, the Finnish repository project started safeguards consideration by collaboration with IAEA (Okko and 2003 May.).

In OTDD, spent fuel canisters are placed in a geological repository while the radiation level is still high, and the spent fuels are isolated in a deep geological formation after the final closure of the repository. Thus, the loss of radiation barrier could be somehow “compensated” by the geological barrier. In the case of LHR, the situation could potentially be more concerned because of its lower level of radiation immediately after the separation. After LHR is disposed of in a repository and the repository is finally closed, the level of protection would be comparable to that for direct disposal of spent fuel, while the repository is still subject to safeguards inspection by IAEA. If LHR is further separated and TRU is transmuted by a nuclear reactor, the proliferation concern for the final disposal over the millennia could be eliminated, but the proliferation concern during the process of TRU separation and transmutation with SFR arises.

Appendix B. Convergence of HHR waste

We consider a mathematical model for evolution of the mass of HHR isotopes with time by assuming three conceptualized stages of nuclear power utilization: (1) the expansion stage, (2) the equilibrium stage, and (3) the phase-out stage, as depicted in Figure B.1.

The governing equation for the accumulated quantity $\hat{M}(\hat{t})$ [mols] of the HHR isotopes (Cs-137 and Sr-90) at time $\hat{t}$ [yr] generated by operating a fleet of nuclear reactors in a country can be written as:

$$\frac{d\hat{M}}{d\hat{t}} = \hat{q}(\hat{t}) - \hat{\lambda}\hat{M}, \text{ subject to } \hat{M}(0) = 0, \quad (\text{B.1})$$

where

$$\hat{q}(\hat{t}) = \begin{cases} \hat{Q}\exp(\hat{c}\hat{t}), & 0 < \hat{t} \leq \hat{t}_1 \\ \hat{k}, & \hat{t}_1 < \hat{t} \leq \hat{t}_2 \\ \hat{k} \frac{\hat{t}_3 - \hat{t}}{\hat{t}_3 - \hat{t}_2}, & \hat{t}_2 < \hat{t} \leq \hat{t}_3 \\ 0, & \hat{t} > \hat{t}_3 \end{cases}, \text{ depicted in Figure B.1,} \quad (\text{B.2})$$

$\hat{\lambda}$ the decay constant [1/yr] of the HHR isotopes, $\hat{k} \equiv \hat{Q}\exp(\hat{c}\hat{t}_1)$, $\hat{Q}$ the HHR isotope generation rate [mol/yr] from a unit nuclear power plant, $\hat{c}$ the rate constant of increase of the nuclear capacity [1/yr], $\hat{c} > 0$.

We introduce the following normalization:

$$t \equiv \frac{\hat{t}}{\hat{t}_{1/2}}, \quad \hat{\lambda} = \frac{\ln 2}{\hat{t}_{1/2}}, \text{ thus } \hat{\lambda}\hat{t} = t \ln 2 \text{ and } \hat{c}\hat{t} = \xi t \ln 2, \text{ where } \xi \equiv \frac{\hat{c}}{\hat{\lambda}}, \quad (\text{B.3})$$

$$M(t) \equiv \frac{\hat{M}(\hat{t})}{\hat{t}_{1/2}\hat{Q}}, \quad k \equiv \frac{\hat{k}}{\hat{Q}} = \exp(\hat{c}\hat{t}_1) = \exp(\xi t_1 \ln 2), \text{ and} \quad (\text{B.4})$$

$$q(t) = \begin{cases} \exp(\xi t \ln 2), & 0 < t \leq t_1 \\ k, & t_1 < t \leq t_2 \\ k \frac{t_3 - t}{t_3 - t_2}, & t_2 < t \leq t_3 \\ 0, & t > t_3 \end{cases} \quad (\text{B.5})$$

The quantity $\hat{t}_{1/2}$ is the half-life [yr] of the HHR isotopes, 30 years.

The governing equation in terms of the normalized quantity is written as

$$\frac{dM}{dt} = q(t) - (\ln 2)M, \text{ subject to } M(0) = 0. \quad (\text{B.6})$$

The solution for this is obtained as follows:

$$(\text{expansion}) M(t) = \frac{1}{(\xi + 1)\ln 2} \{ \exp(\xi t \ln 2) - \exp(-t \ln 2) \}, \quad 0 \leq t \leq t_1 \quad (\text{B.7})$$

$$(\text{equilibrium}) M(t) = M_1 \exp(-(t - t_1)\ln 2) + \frac{k}{\ln 2} \{ 1 - \exp(-(t - t_1)\ln 2) \}, \quad t_1 \leq t \leq t_2 \quad (\text{B.8})$$

$$(\text{phase - out}) M(t) = M_2 \exp(-(t - t_2)\ln 2) + \frac{k}{\ln 2} \{ 1 - \exp(-(t - t_2)\ln 2) \} - \frac{k}{t_3 - t_2} \times \left[\frac{t - t_2}{\ln 2} - \frac{1 - \exp(-(t - t_2)\ln 2)}{(\ln 2)^2} \right], \quad t_2 \leq t \leq t_3 \quad (\text{B.9})$$

$$(\text{Post phase - out}) M(t) = M_3 \exp(-(t - t_3)\ln 2), \quad t \geq t_3 \quad (\text{B.10})$$

$$\text{where } M_1 \equiv \frac{1}{(\xi + 1) \ln 2} \{ \exp(\xi t_1 \ln 2) - \exp(-t_1 \ln 2) \}, \quad (\text{B.11})$$

$$M_2 \equiv M_1 \exp(-(t_2 - t_1) \ln 2) + \frac{k}{\ln 2} \{ 1 - \exp(-(t_2 - t_1) \ln 2) \}, \text{ and} \quad (\text{B.12})$$

$$M_3 \equiv M_2 \exp(-(t_3 - t_2) \ln 2) + \frac{k}{\ln 2} \{ 1 - \exp(-(t_3 - t_2) \ln 2) \} - \frac{k}{t_3 - t_2} \left\{ \frac{t_3 - t_2}{\ln 2} - \frac{1 - \exp(-(t_3 - t_2) \ln 2)}{(\ln 2)^2} \right\} \quad (\text{B.13})$$

We assume that $\xi = 4$. This is the growth rate of nuclear power capacity in the expansion stage. The length t_1 of the expansion stage is assumed to be 1.5. The value of k is calculated to be 64. With these values, in the expansion stage, the capacity of the nuclear reactor fleet grows to 64 times of the unit capacity in 45 years. The unit capacity can be taken to be the capacity of the reactor first introduced. We consider the cases shown in Table B.1.

The cumulative mass monotonically increases, and approaches an upper bound value asymptotically (see (B.8)). This is shown by the curves for Cases 1 and 2 in Figure B.2. As the phase-out stage becomes longer, the cumulative mass at the end of the phase-out stage is smaller.

Table B.1
Cases for HHR Generations and Build-up.

	t_1	t_2	t_3	
Case 1	1.5	10	11	Long equilibrium; short phase-out
Case 2		10	12	Long equilibrium; twice long phase-out
Case 3		5	6	100 year equilibrium; short phase-out
Case 4		2.5	3.5	Short equilibrium; short phase-out
Case 5		2.5	12.5	Short equilibrium; 300-year phase-out

Figure A.1. Dose for 8 h at 1 m location from the spent fuel package for the Yucca Mountain Repository.

Figure B.1. Three conceptualized stages of nuclear-power deployment and utilization.

Figure B.2. Cumulative mass of HHR isotopes for different scenarios as a function of normalized time.

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