The economic effects of the deferred disposal of spent fuel in Korea

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The present study analyzes the economic effects concerning deferred disposal of spent fuel through long-term storage. According to the cost analysis, a scenario that a 90-year deferral of an HLW (High-Level Waste) repository construction in favor of a long-term storage of spent fuel would be economically preferable to another scenario based on the year 2040 chosen as the starting point for construction on a repository. That is, the former scenario would cost about 1/2 of the latter. This finding is an estimated result from an economic perspective only, assuming the disposal of 20,000-ton PWR spent fuel and 16,000-ton CANDU spent fuel. Still, it seems necessary to elicit proper term of storage for radioactive waste in order to comply with the so-called Polluter-Pays principle that the current generation cannot pass on its radioactive waste to the next generation.

1. Background

Deferral of the Yucca Mountain repository construction in the U.S. has led worldwide nuclear energy superpowers to review the feasibility of long-term storage of spent fuel. Technically, the long-term storage of spent fuel in Korea is under consideration, to begin with direct disposal of the nuclide from 129I could risk human ecosystems. According to the safety assessment of Korea’s KRS repository concept, direct disposal of spent nuclear fuel produced in Korea will result in iodine-129 nuclide reaching human ecosystems at the speed of underground water flow from the underground HLW repository. A case could occur where a disposal canister corrodes due to its very low adsorption coefficient in relation to the granitic bedrock which serves as a natural buffer and barrier. That is, 129I nuclide could appear in human ecosystems very quickly compared with other nuclides and it has been found the most hazardous nuclide due to an extremely long half-life (Kang et al., 2000). Consequently, the biggest concern for Korea is how best to dispose of 129I. As an alternative to this matter, an advanced nuclear fuel cycle, where PWR-based spent nuclear fuel undergoes pyroprocessing, and the uranium and TRU which is produced in the process are recycled in a fast reactor, is being studied. In other words, as a proposed solution to deal with 129I, the remaining 129I in the spent nuclear fuel is put into the fast reactor and burnt. Accordingly, in regard to the repository safety, a plan to defer the disposal of spent nuclear fuel until a fast reactor is built is suggested as a very acceptable measure.

Second, domestically, studies on the pyroprocessing are underway and the back-end fuel cycle option has not been determined. Thus, until the back-end fuel cycle option is determined, spent fuel needs be managed. For that reason, long-term storage of spent fuel is required before a fast reactor is built so that the uranium and TRU recovered from the pyroprocessing can be recycled as the fast-reactor fuel.

In general, the back-end fuel cycle is divided into direct disposal and reprocessing (OECD/NEA, 2006), but considering the current deferral of the repository construction for spent fuel, the long-term storage before disposal can be added as an alternative.

Countries capable of reprocessing spent fuel take into account interim storage of HLW reduced in volume through reprocessing for a certain period of time before final disposal, whereas other countries with no reprocessing facility are concerned about how to reduce the volume of radioactive waste for safe disposal of spent nuclear fuel.

At present, Korea relies on dry and wet storage in NPPs (Nuclear Power Plants) for interim storage of spent fuel. Unfortunately, the capacity of these storage facilities for spent nuclear fuel is expected to be saturated by 2016. Hence, plans are drawn up to install high-density storage racks in the temporary storage pools in NPPs or to expand the capacity of facilities to take in spent fuel. However,
safety concerns of the high-density storage rack is under review on account of the disaster in the spent fuel pools at the NPP in Fukushima, Japan.

Moreover, as Korea is incapable of reprocessing spent fuel with the wet processing method, direct disposal and pyroprocessing are being investigated. In particular, recent studies have been actively conducted on the advanced nuclear fuel cycle which allows PWRs (Pressurized Water Reactors) to be connected with fast reactors via pyroprocessing.

Nevertheless, as Korea has no fast reactor yet and sodium fast reactors are still under development, the long-term storage of spent fuel has been raised as a must alternative worth considering, in order to manage the matter.

Besides, building fast reactors is closely related to nuclear energy policies in Korea, so technical and economic feasibility of the advanced nuclear fuel cycle in reference to pyroprocessing and energy policies in Korea, so technical and economic feasibility of the advanced nuclear fuel cycle in reference to pyroprocessing and fast reactors need to be supported. That is, whether the plan to process $^{129}$I and recycle the uranium and TRU is technically and economically feasible and is an efficient alternative needs to be clarified first.

This study aims to analyze the economic effects of the deferred disposal of spent fuel by hypothesizing three direct-disposal scenarios. Namely, investment costs are comparatively analyzed based on three scenarios set, assuming that spent fuel will be disposed of after 30, 90 and 190 years. The assumed deferral terms of disposal are based on the estimated reasonable points in time for disposal of spent fuel by accounting for the current capacity of spent fuel pools in Korea and its plans to develop fast reactors into consideration.

However, these long-term storage scenarios go against the IAEA’s Polluter-Pays principle applied to radioactive waste. In the case that the disposal of spent fuel is deferred by the long-term storage, future generations are to bear the financial burden for disposal of radioactive waste even though they are irrelevant to radioactive waste produced for the benefit of us. After all, risks and burdens due to radioactive waste are passed on to generations to come. Currently, however, radioactive waste cannot be disposed of within years, nor can we rely on limitless deferral, so it is hard to suggest a particularly good alternative to manage spent fuel. Considering the current status, there is no disposal of spent fuel within 30 years.

Thus, in view of the alternative based on the back-end fuel cycle, it is not reasonable to analyze the direct disposal within short-term only. Further, to analyze economic feasibility of the alternative based on the back-end fuel cycle, both the long-term storage costs and disposal costs of spent fuel must be considered as the costs for long-term storage and disposal are closely related (OECD/NEA, 1994).

For example, in the case that interim storage period increases, leading to the state of long-term storage, the construction of a repository is deferred, while interim storage cost grows and the repository construction cost declines because of the time value of currency (Salomon, 2009). Therefore, tradeoffs may exist between long-term storage cost and the investment cost for repository construction. In that sense, it is wrong to determine economic feasibility of an alternative by separating long-term storage cost from disposal cost, and a right decision can be made on a certain alternative when costs for long-term storage and disposal are tallied to find out economic feasibility.

Also, deferred disposal of spent fuel may reduce the amount of money owed due to low-cost investment cost in construction, while it is not easy to estimate accurate back-end fuel cycle cost due to inflation arising during the deferral term. Still, as the long-term storage facilities are not built on the deep-seated bedrock, the investment cost for construction of such storage facilities is likely to be smaller than that for conventional HLW repository construction, and the uncertainty in cost estimation of storage facilities is probably low. Assuming the underground repository requires drilling deep-seated granitic rocks to build disposal tunnels and disposal holes, it is hard to estimate the cost of drilling as Korea has never constructed disposal tunnels and holes in such deep-seated bedrocks (Saanio and Kokko, 2007).

From the perspective of major cost drivers, a big difference may exist between long-term storage casks and disposal canisters (Saegusa et al., 2008). Considering the A-KRS method for underground disposal of spent fuel, the outer part of disposal canisters must be applied with 1-cm-thick copper coating which is highly corrosion-resistant to deep-seated underground water. Then, the material cost for disposal canisters is likely to grow much higher than that for interim storage casks (Kim et al., 2007).

After all, long-term storage will cost less than disposal. Yet, long-term storage cost is not negligible, so it is reasonable to choose an alternative by taking costs of both long-term storage and disposal into account.

The present study covers the cost estimation of the back-end fuel cycle for long-term storage and disposal, respectively, on a constant cost basis following 3 scenarios of the deferral of HLW repository construction to present economic effects of the deferred disposal of spent fuel disposal at different points in time.

For cost estimation, relative economic feasibility of each of three scenarios is analyzed based on the sum of long-term storage cost due to deferral of HLW repository construction and repository construction cost.

In short, as the back-end fuel cycle induces a large cost in the future, the sum of disposal and long-term storage costs estimated as constant costs or values is converted into present values using appropriate real discount rates. Further, based on the findings, the economic feasibility of each scenario is analyzed to choose an appropriate alternative.

2. Cost estimation

2.1. Technical and economic data

To estimate the economic effects of the deferral of disposal, technical and economic terms need considering. Technical terms refer to conditions needed to meet the design requirements of interim and long-term storage facilities, while economic terms are associated with the assessment methods and parameters used to estimate costs.

In the present study, engineering cost estimation is used based on the conceptual design of facilities. To be more specific, cost drivers of facilities are determined to sum up the costs based on the unit prices and material volumes in a bottom-up method.

Essentially, for the estimation approach adopted here, technical requirements for the conceptual design of each facility need to be identified. Therefore, technical conditions related to each facility required of the cost estimation of interim storage and repository need to be established. For example, the volume of spent fuel that a long-term storage facility or the repository could take in is an example of such technical conditions.

The capacity of a facility needs estimating with the volumes of spent fuel considered. Fig. 1 shows the arising volumes of spent fuel generated in Korea.

Once the repository’s capacity to take in spent fuel is determined, the size of the underground disposal facility can be decided and the time of construction and operation can be estimated. In particular, as repository construction and operation takes a long time, the period to construct a repository can be an important factor in cost estimation. If repository construction runs parallel with operation, the investment cost for construction and operation
can be reduced, in which sense it is a must to perform an in-depth analysis of proper periods needed for repository construction and operation. Following the findings regarding the concept of KRS disposal in a previous study, which was conducted in conjunction with Posiva in Finland, this study assumes the repository construction and operation are run in parallel for a total of 80 years (Kukkola and Saanio, 2003).

To sum up, the primary technical conditions needed to see the economic effects of the deferral of disposal are as follows.

First, the long-term storage is assumed to apply to storage of spent fuel on power plant sites, whereas the direct disposal is considered applicable to vertical disposal in 500-m underground granitic rocks. Second, the objects of disposal cost are limited to the deep geological repository with disposal capacity covering PWR spent fuel (20,000 tons) and CANDU spent fuel (16,000 tons) on the assumption that the PWR’s initial enrichment is 4.5% and its burn-up is 55 GWD/MtU. Third, the cooling time is assumed to last for 10 years. Fourth, the period of deferred disposal is assumed to be the time for the long-term storage of spent fuel.

For the comparative analysis of economic feasibility, the following economic terms are assumed. First, all cost has been applied with a real discount rate and calculated as a constant cost as of the end of 2010. Second, the prices marked as nominal values referred to in literature are converted into prices as of 2010 based on 2.3% of inflation rate and 4.36% of nominal discount rate (Samil Accounting Firm, 2003), both of which are specified in the Korean radioactive waste law. Third, the values used to estimate the cost of KRS repository are applied to the repository-related unit costs.

### 2.2. Ellicitation of input parameters

Parameters mostly used to assess the cost of back-end fuel cycle include inflation and discount rates. Differently put, as the disposal cost of radioactive waste arises in an impending future, estimated cash flow is calculated as the future value as of the point in time that the repository is built, and then appropriate discount rates are applied to convert the results into the present cost at the assessment point in time.

Subsequently, in the case that cash flow is represented as a nominal value, inflation rates and discount rates may not be applied equally. For example, in contrast to inflation rates, discount rates may reflect the credit risks of a company in charge of disposal projects.

#### 2.2.1. Appropriate inflation rate

In scenario 1, the inflation rate for the 30-year period is reflected in the disposal project. So it is desirable to use the mean growth rates of PPI (Producer Price Inflation) over the past 30 years or more as the appropriate inflation rate as in Eq. (1).

$$EER = \sum_{t=1}^{n} \frac{HER_t}{n}$$

Where, EER = Estimated escalation rate, HER_t = Historical escalation rate at t years. In Korea, the mean inflation rate for 44 years from the 1960s is 2.3%. Accordingly, to estimate the future value of the radioactive waste fund in Korea, 2.3% of inflation rate is applied. In contrast, inflation rates for advanced countries such as the US and France are reported at 1.8% are lower than the mean inflation rate for Korea.

#### 2.2.2. Appropriate discount rate

The longer long-term storage in relation to the back-end fuel cycle, the farther the point in time for repository construction is prolonged from the present. Therefore, discount rates are important in converting the investment cost of repository construction.

Overestimated discount rates would underestimate the present value of the investment cost of repository construction, whereas underestimated discount rates would overestimate the present value of the investment cost of repository construction. Thus, it is important to derive an appropriate discount rate in disposal cost estimation.

In general, market interest rates or effective interest rates are used for the discount rates. According to the K-GAAP (Generally Accepted Accounting Principles) No. 5 (tangible assets), discount rates need estimating by considering risk-free interest rates and credit risks of entities in charge of each project (Korean Accounting Institute, 2004).

Based on the disposal scenario 1, the point in time for repository construction is 2041, so the discount period is 30 years. Accordingly, it is advisable to apply the discount rates of long-term (over 30 years) bonds. However, Korea offers no 30-year government or public bonds but 10-year bonds do exist. Consequently, to estimate the appropriate discount rate as in Eq. (2), 10-year interest rates of government and public bonds, 20-year risk term and the credit risks of organizations in charge of disposal projects as well as reset margins are added up here.

$$ED_t = IRNB_{10 \ yr} + RP_{20 \ yr} + KRMC_{cr} + AIR$$

Where, $ED_t$ = Estimated Discount rate, $IRNB_{10 \ yr}$ = Interest rate of national bond for 10 years, $RP_{20 \ yr}$ = Risk of period for 20 years, $KRMC_{cr}$ = Credit risk of KRMC (Korea Radioactive Waste Management Corporation), AIR = Additional Interest Rate.

In Eq. (2), the 20-year risk term can be calculated indirectly in reference to the interest rates of the U.S. government and public bonds as in Eq. (3). That is, the calculated value based on the interest rate ratios between the U.S. 30-year and U.S. 10-year government and public bonds is multiplied by the interest rate of Korea 10-year government and public bonds.

$$RP_{20 \ yr} = KBI_{10 \ yr} \left( \frac{USBI_{30 \ yr}}{USBI_{10 \ yr}} - 1 \right)$$
Where, USBI30 yr = Interest rate of U.S. national bond with maturity of 30 years, USBI10 yr = Interest rate of U.S. national bond with maturity of 10 years, KBI30 yr = Interest rate of Korea national bond with maturity of 10 years.

In the Eq. (2), KRMC’s credit risk can be calculated by deducting the 5-year interest rate of government and public bonds from the market returns on 5-year corporate bonds as in Eq. (4).

\[ \text{KRMC}_{cr} = \text{MR}_{5 \text{ yr}} - \text{IRNB}_{5 \text{ yr}} \]

Where, MR5 yr = Market revenue of KRMC bond with maturity of 5 years, IRNB5 yr = Interest rate of Korea national bond with maturity of 5 years.

In sum, using Eqs. (2)–(4), the appropriate discount rate can be derived.

2.3. Cost estimation method

For direct disposal of spent nuclear fuel, the back-end fuel cycle cost in each scenario equals to the sum of long-term storage costs and deep geological disposal costs. To calculate the costs, therefore, the concepts of long-term storage and deep geological disposal need defining. That is due to the present study using engineering cost estimation. For example, based on the conceptual design of a repository facility, unit costs and volumes of materials for each specific facility are estimated to calculate the disposal cost (AACE, 2004).

As for the repository concept, KAERI (Korea Advanced Energy Research Institute) is developing a vertical disposal concept of spent nuclear fuel by drilling 500-m underground granitic rocks to build disposal tunnels and holes (Kukkola and Saanio, 2003).

KRS (Korean Reference System), which disposes of PWRs and CANDU spent fuel, is adopted as the cost object for the cost estimation (Saanio et al., 2004).

KAERI has developed the KRS disposal concept into A-KRS, which concept takes different disposal approaches depending on the types of spent fuel. That is, CANDU spent fuel is subject to direct disposal, whereas PWR spent nuclear fuel undergoes pyroprocessing as part of the disposal strategy to reduce the volume of radioactive waste and the land area for a repository. The reason to take the strategic direct disposal approach of CANDU spent fuel is that CANDU initial enrichment of spent fuel is lower than that of the cost of uranium recovered from pyroprocessing and economically impracticable.

Pyroprocessing cost is currently being studied. Hence, the present study does not consider the pyroprocessing cost but examines the economic feasibility of the direct disposal based on 3 scenarios of deferred repository construction.

The cost effects due to deferral of repository construction on each scenario can be expressed as in Eq. (5).

\[ \Delta C_{\text{deferral}} = \left( c_i + c_{k} \right) - \left( c_{i+k} + c_{k} \right) \]

Where, \( K \) = The deferred period of HLW repository construction.

Eq. (6) expresses the nominal future value, representing the investment cost as of the point in time that construction of an underground HLW repository is completed.

\[ FC = \sum_{i=1}^{T} C_i (1 + r)^{T-i} \]

Where, \( r \) = nominal interest rate, \( T \) = The completed year of construction.

Meanwhile, Eq. (7) is about the nominal interest rate.

\[ r = \left( 1 + f \right) \left( 1 + \bar{r} \right) - 1 \]

Where, \( \bar{r} \) = real interest rate, \( f \) = Inflation rate. Therefore, the real discount rate is estimated as in Eq. (8).

\[ \bar{r} = \frac{(1 + r)}{(1 + f)} - 1 \]

In short, the real interest rate is the nominal interest rate deflated with inflation rate (Hwang, 2005). Accordingly, applying Eq. (7) to Eq. (6) results in Eq. (9):

\[ FC = \sum_{i=1}^{T} C_i (1 + \bar{r})^{T-i} \left( 1 + f \right)^{T-i} \]

As in Eq. (9), the effects of parameters affecting the cost are largely composed of inflation rates and interest rates.

3. Long-term storage cost

Long-term storage cost refers to every expense spent to manage radioactive waste safely in interim storage facilities prior to disposal of spent fuel in a deep geological repository or reprocessing (Nagano, 2008).

Currently, Korea has no independent interim storage facility, so spent fuel goes to wet and dry temporary storage facilities in NPPs on the premises. Hence, the long-term storage cost scenarios may largely consider two ways. The first scenario is to expand and improve on-site interim storage facilities for long-term storage, and the other scenario is to build off-site interim storage facilities (Silva et al., 2008).

This study assumes that for long-term storage of spent nuclear fuel, old storage racks in current wet temporary storage facilities on the premises are improved on or replaced with added high-density storage racks.

The reason to expand the on-site wet temporary storage facilities is that the capacity of each temporary storage facility on the premises in Korea is expected to reach its limits at the end of 2016. As seen in Table 1, spent fuel generated in domestic power plants is stored at 4 sites on the premises. The Gori power plant’s temporary storage facility will be saturated in 2016, and at the latest in 2021 the entire capacity of current domestic temporary storage facilities will reach its limits. Thus, for long-term storage of spent fuel in temporary storage facilities on the premises, those facilities need improving and expanding to increase the capacity to store spent fuel.

Alternatively, pyroprocessing can be used to significantly reduce the volume of radioactive waste, but as studies on the pyroprocessing are underway at present, the present study excludes the disposal cost of nuclear waste using the pyroprocessing.

The primary cost drivers of long-term storage largely include casks containing spent fuel, storage facilities and land. In short, the construction cost including the land cost and the operating cost

<table>
<thead>
<tr>
<th>Table 1</th>
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</thead>
<tbody>
<tr>
<td>Capacity of temporary storage in nuclear power plant.</td>
</tr>
<tr>
<td>NPPs (Sites)</td>
</tr>
<tr>
<td>Gori</td>
</tr>
<tr>
<td>Yeonggwang</td>
</tr>
<tr>
<td>Uljin</td>
</tr>
<tr>
<td>Wolsung</td>
</tr>
</tbody>
</table>
Including the cask cost are primary cost drivers of the long-term storage cost. These costs are easily and conservatively calculated using the unit module concept. Specifically, the long-term storage cost per unit consumed per storage cask is multiplied by the number of casks. Otherwise, the unit price of the long-term storage cost per unit consumed per storage cask is multiplied by the material volume to estimate the long-term storage cost.

Here, as in Eq. (10), the unit cost was applied to the cost estimation. Using interim storage scenarios as in Table 2, and interim storage volumes as in Table 3, the interim storage cost is estimated as in Table 4. To summarize, the unit costs of long-term storage of spent fuel in interim storage facilities for PWR spent fuel and CANDU spent fuel based on the storage capacity of 20,000-ton PWR spent fuel and 16,000-ton CANDU spent fuel are estimated to be approximately 150 EUR/kgHM and 54 EUR/kgHM, respectively. In this estimation, concrete casks were assumed for CANDU spent fuel.

\[
\text{CLS} = \sum_{i=1}^{T} \left( \frac{UC_{is}}{(1 + d)^{T-i}} \right) \times MV_{sf}^{is}
\]

Table 2
Alternatives of interim storage.

<table>
<thead>
<tr>
<th>Category</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1-1</td>
<td>Change storage rack (The replacement of storage rack): Yeonggwang Unit 2</td>
</tr>
<tr>
<td>A 1-2</td>
<td>Add storage rack (The supplement of storage rack): Shingori Unit 1, 2</td>
</tr>
<tr>
<td>A 2</td>
<td>Transport inter-site (Transportation between sites): Gori-Shingori, Uljin-Shinuljin</td>
</tr>
<tr>
<td></td>
<td>Dry storage in site (inter-site transportation): Wolsung</td>
</tr>
<tr>
<td></td>
<td>Number of interim storage sites: 2 (Wolsung and 1 AFR)</td>
</tr>
<tr>
<td></td>
<td>The replacement of storage rack: Yeonggwang Unit 2</td>
</tr>
<tr>
<td></td>
<td>Add storage rack (The supplement of storage rack): Shingori Unit 1, 2</td>
</tr>
<tr>
<td></td>
<td>Transport inter-site: Gori-Shingori (2016), Uljin-Shinuljin</td>
</tr>
<tr>
<td></td>
<td>Dry storage in site: Wolsung, Gori</td>
</tr>
<tr>
<td></td>
<td>Number of interim storage sites: 3 (Wolsung, Gori and 1 AFR)</td>
</tr>
<tr>
<td></td>
<td>The replacement of storage rack: Yeonggwang Unit 2</td>
</tr>
<tr>
<td></td>
<td>Add storage rack (The supplement of storage rack): Shingori Unit 1, 2</td>
</tr>
<tr>
<td></td>
<td>Inter-site transport: Gori-Shingori (2016)</td>
</tr>
<tr>
<td></td>
<td>Dry storage in all site will be introduced step by step</td>
</tr>
<tr>
<td></td>
<td>Number of interim storage sites: 7 (all sites)</td>
</tr>
</tbody>
</table>

Table 3
Material volume of interim storage.

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Inter-site transportation</th>
<th>Interim storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Transported volume (ton)</td>
<td>On-site (ton)</td>
</tr>
<tr>
<td>A 1-1</td>
<td>1206</td>
<td>3179 (CANDU)</td>
</tr>
<tr>
<td>A 1-2</td>
<td>673</td>
<td>533 (PWR)</td>
</tr>
<tr>
<td>A 2</td>
<td>176</td>
<td>7140 (PWR)</td>
</tr>
</tbody>
</table>

Table 4
Estimated investment costs of interim storage by 2040 [Unit: MEUR].

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Replacement of the rack and transportation at inter-site</th>
<th>Transportation from NPP site to out-site interim storage</th>
<th>Investment costs (on-site and out-site)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1-1</td>
<td>74</td>
<td>142</td>
<td>595</td>
<td>811</td>
</tr>
<tr>
<td>A 1-2</td>
<td>60</td>
<td>140</td>
<td>652</td>
<td>852</td>
</tr>
<tr>
<td>A 2</td>
<td>43</td>
<td>–</td>
<td>734</td>
<td>777</td>
</tr>
</tbody>
</table>

Table 5
The unit cost of disposal canister.

<table>
<thead>
<tr>
<th>Type of canister</th>
<th>Cu_{t} (mm)</th>
<th>Manufacturing method of outer canister</th>
<th>Cost estimation (kEUR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR50</td>
<td>50</td>
<td>Forging</td>
<td>216</td>
</tr>
<tr>
<td>PWR</td>
<td>10</td>
<td>CSC</td>
<td>88.5</td>
</tr>
</tbody>
</table>

Where, CLS = Cost of long-term storage, UC_{is} = Unit cost of long-term storage, MV_{sf}^{is} = material volume of spent fuel at t (year), d = real interest rate.

4. Disposal cost

For the repository cost, the life cycle is considered and the term of the construction and operation is assumed to be 80 years, while the cost structure consists of construction, operation and closure costs. Notably, an HLW repository requires long-term construction projects, which is why construction is run in congruence with operation. Here, operation refers to taking over the disposal canisters loaded with spent fuel to inspect them in a ground facility of a repository and deploying them in disposal holes in underground facilities. Therefore, disposal cost is largely applicable to ground and underground facilities, and the ground cost may be subdivided into expenses in relevance to construction, operation and closure.

 Particularly, the cost of disposal canisters accounting for the highest percentage of disposal cost is attributed to the operating cost of the ground facility (Kukkola, 2005). Table 5 shows the unit cost of disposal canister developed so far for PWR-spent fuel.

Prior studies have found that disposal canisters are the largest cost drivers in terms of the disposal cost of spent fuel, and specifically, copper is the primary cost driver in relation to the cost of disposal canisters (AECL, 2006).

Here, to estimate the disposal cost, engineering cost estimation based on the conceptual design of a repository is used and the overnight cost for each construction phase of the repository is calculated. This study, as in Fig. 2, estimates the cash flow of each construction phase of the repository (Kukkola and Saanio, 2003).

Accordingly, the cash flow of each construction phase is estimated and converted into the present value. So, it is a necessity to
use the appropriate discount rate in converting the estimated value into the present one in order to get an accurate disposal cost.

5. Results of cost estimation on deferral of disposal

To find out the economic effects of the deferral of repository construction, three scenarios at three points in time as in Fig. 3 are assumed here. The terms of deferred repository construction are the number of years as from the present to the repository construction. For example, 2041 in the first scenario means that the repository construction is deferred for 30 years from now, and 2101 means that it is deferred for 90 years till 2101.

To be more specific, the first scenario assumes the spent fuel remains until 2040 in an interim storage before disposal in a repository whose construction begins in 2041. The second scenario assumes the spent fuel is kept until 2100 in a long-term storage and the construction of the repository begins in 2101. Lastly, spent fuel is stored in a long-term storage till 2200 before the repository is built.

The reason why the first scenario chooses 2041 as the start year of the repository construction is that current domestic dry and wet storage facilities are going to be saturated with spent fuel in 2016, so although the high-density strategy is adapted to storage facilities, disposal must be done in 2040 at the latest unless the spent fuel is reprocessed.

To build an independent central interim storage for spent fuel could defer the start year of the repository construction to a great extent.

To estimate the total cost of each scenario, the cost of long-term storage and that of disposal are calculated from the starting point of the repository construction.

Table 6 shows the results of the cost estimation following the deferred disposal in each scenario in reference to long-term storage costs and disposal costs of underground HLW repository.

As in Table 6, construction deferred up to 2101, compared to the 2041-based scenario, could reduce the cost at the least by more than 1/2. Also, repository construction deferred up to 2201, compared to the 2041 scenario, would reduce cost equivalent to about 1/2 of the back-end fuel cycle cost.

These findings are ascribable to, first, the cost-reduction effects following the time values of construction cost resulting from the deferred repository construction. Second, the discount rates applied here are higher than inflation rates. Such higher discount rates are applied in compliance with the Korean law on radioactive waste management, stipulating 4.36% of a discount rate. Also, technically, over time the decay heat of radioactive waste decreases and radioactive nuclides with shorter half-lives reduce, leading to lower cost of constructing a radiation-shielding facility (Miklos and Slugen, 2008).

The fact that deferred repository construction may lower investment costs does not necessarily warrant unconditional deferral of repository construction on these grounds. First, in compliance with the Polluter-Pays principle, we must take care of the radioactive waste we have produced (IAEA, 2002). Second, long-term deferral of a repository construction may have disagreeable influences on the national sentiment of spent fuel. Namely, national trust in government policies to manage spent fuel
could decline. As a consequence, in lieu of infinite deferral of an HLW repository, it seems desirable to consider current capacity of all storage facilities for spent fuel, the volume of spent fuel generated and the construction plans of interim storage facilities so as to determine the starting point of building an HLW repository.

For this study, the optimal storage period of HLW was estimated by using annual investments and long-term storage costs at a nominal discount rate of 4.36% as shown on Fig. 4. Economically, it was found, from a conservative viewpoint, that HLW might be expected to continue storing until 2090. However, the construction of an HLW repository should begin by 2090 at the latest.

6. Conclusion

Throughout the world, construction of repositories for spent fuel tends to be deferred due to the deferral of the Yucca Mt. repository in the U.S. In that sense, the present study analyzes the economic effects of deferred construction of a repository. For the economic feasibility analysis, the direct disposal of back-end fuel cycle is assumed, and three scenarios are set based on three points in time for starting repository construction (2041, 2101 and 2201). Furthermore, the long-term and disposal costs of each scenario are calculated to estimate the total cost of the back-end fuel cycle, which is, in turn, used for a comparative analysis of the economic feasibility of each scenario.

According to the analysis, if a repository is built in 2101 instead of 2041, the total cost reduces to about 1/2. This is attributable to the time values of money as well as the higher unit cost of direct disposal. In a manner of speaking, the longer the term storage, the lower the construction cost.

Finally, from the aspect of economic sense, it was found that the construction of an HLW repository should begin by 2090 at the latest. Technically, the decreasing decay heat of radioactive waste due to the long-term storage leads to less strict requirements of radiation-shielding facility designs (Matsumura et al., 2008), resulting in less investment in construction of a repository.

Nevertheless, the long-term storage scheme potentially goes against the Polluter-Pays principle advocated by the IAEA and the like. Essentially, we must dispose of the radioactive waste we have produced so that the following generations can be free of any burden due to disposal of radioactive waste.

Moreover, the long-term storage studied here involves the temporary storage facilities on the premises of NPPs which proves contradictory in that spent nuclear fuel remains even after the life spans of NPPs come to an end. However, such a limitation is ignored here for the sake of the economic feasibility analysis with reference to the deferred disposal of spent fuel.

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