Research Article

Economic Viability of Metallic Sodium-Cooled Fast Reactor Fuel in Korea

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Received 7 November 2012; Revised 18 February 2013; Accepted 19 February 2013

Academic Editor: Michael F. Simpson

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This paper evaluates whether SFR metallic nuclear fuel can be economical. To make this determination, the cost of SFCF (SFR fuel cycle facilities) was estimated, and the break-even point of the manufacturing cost of SFR metallic nuclear fuel for direct disposal option was then calculated. As a result of the cost estimation, the levelized unit cost (LUC) for SFCF was calculated to be 5,311$/kgHM, and the break-even point was calculated to be $5,267/kgHM. Therefore, the cost difference between LUC and the break-even point is not only small but is also within the relevant range of the uncertainty level of Class 3 in accordance with a generic cost estimate classification matrix of AACE (the Association for the Advancement of Cost Engineering). This means it is very difficult to judge the economical feasibility of SFR metallic nuclear fuel because as of today there are no commercial facilities in Korea or the world. The economic feasibility of SFR metallic nuclear fuel, however, will be enhanced if the mass production of SFCF becomes possible in the future.

1. Introduction

Since the accident in the nuclear power plant in Fukushima, Japan, occurred, some advanced countries are attempting to better manage their nuclear power generation and spent fuel. In addition, these countries are carrying forward the development of alternative energy such as solar heat and wind power; however, for now there is no appropriate alternative electric power production that can substitute for nuclear energy. For now, there are limitations for alternative energy to replace nuclear energy, and for the recycling of uranium the method of recycling spent fuel accumulated in nuclear power plants or in intermediate storage facilities in an SFR (sodium-cooled fast reactor) is judged to have sufficient investment value. To develop a sodium-cooled fast reactor (SFR), however, the part that should be reviewed priorly in the aspect of economic feasibility is to judge its economic feasibility and compare it with direct disposal. This is because direct disposal is known to be economical in the alternatives of nuclear fuel cycle. Therefore, it is necessary to calculate the break-even point by comparing the Pyro-SFR nuclear fuel cycle cost, which considers the manufacturing cost of the SFR metallic nuclear fuel, with the direct disposal cost.

Korea is presently operating 21 nuclear power plant units and plans to continuously increase the capacity of nuclear power generation in the future. However, the operation of nuclear power plants inevitably causes the generation of spent fuel. In addition, the capacity of Korea’s present temporary storage facilities for spent fuel will become lower than the required storage capacity in each nuclear power plant site and will reach the saturation condition in 2016.

According to the 2009 yearbook of Korea’s nuclear energy, we have a plan to manage the spent fuel generated from nuclear power plants through the installation of a high density storage rack, the transferring between units, and the installation of a dry storage facility at each nuclear power plant site. Therefore, for continuous increase in nuclear energy, we should fundamentally solve the problem of spent fuel presently accumulated in nuclear power plants. The selection of a site, however, for interim storage or a repository for spent fuel is recognized as a big obstacle. Therefore, to solve the problem of a shortage of natural uranium and
to decrease the scale of a high-level waste repository, the recycling of spent fuel is inevitable. In addition, to increase the efficiency of uranium use, the development of an SFR and SFR fuel cycle facilities (SFCF) is necessary.

Pyroprocess, which is a dry reprocessing method, converts the spent fuel into metal in high-temperature molten salt phase and decreases the volume of the spent fuel to increase its economic feasibility of disposal innovatively [1].

Namely, the technology of the Pyro-SFR nuclear fuel cycle is one of the alternatives that can fundamentally solve the problem of spent fuel management and is known to be an advanced technology with high proliferation resistance [2].

Some experts, however, still have doubt whether Pyro-SFR nuclear cycle technology is feasible in terms of technology know-how and economics. Therefore, to introduce facilities related to the SFR nuclear cycle, not only continuous research on the manufacture process of SFR metallic nuclear fuel but also the review of the economic feasibility of the pyroprocess for SFR spent fuel is required.

This paper defines the design requirements of SFR nuclear fuel manufacturing facilities and calculates the manufacturing cost of SFR nuclear fuel using the engineering cost estimation method. In addition, by comparing the direct disposal cost with the Pyro-SFR nuclear fuel cycle cost, the break-even point of the SFR metallic nuclear fuel manufacturing cost was elicited. This is because the manufacturing cost of SFR metallic nuclear fuel is a major cost driver of the Pyro-SFR nuclear fuel cycle cost.

2. Conceptual Design of SFR Facility

To calculate the break-even point of the manufacturing cost of SFR metallic nuclear fuel, we should first calculate the Pyro-SFR nuclear cycle cost based on Figures 1 and 2, and to do this we should estimate the cost of the manufacture facilities of the SFR nuclear fuel. Therefore, a conceptual design of SFR facilities as shown in Figure 1 is necessary. The engineering cost estimation method using a conceptual design is for now a realistic method with high reliability [3] and can calculate the cost of SFR nuclear fuel in manufacturing facilities.

We can calculate the cost of investment in the facilities used for SFR nuclear fuel manufacturing, as well as the operation and maintenance cost (O&M) and decontamination and decommissioning (D&D) cost from the bottom up. The cost calculation of SFR metallic nuclear fuel manufacturing is shown in Figure 3.

Table 1: Design standard of SFR fuel cycle facilities.

<table>
<thead>
<tr>
<th>Capacity</th>
<th>32.94 tHM/yr (9.12 tTRU/yr); SF of SFR 6 unit (600 MWe per unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual SFR SF</td>
<td>HM: 38.6t HM/yr, TRU: 11.4 tTRU/yr, annual manufacturing of fuel rod: 327,139/yr, annual fuel assemblies: 1,207/yr</td>
</tr>
<tr>
<td>Manufacturing of SFR new fuel</td>
<td>Plant function: Head-end process, pyroprocess, manufacturing of SFR nuclear fuel</td>
</tr>
<tr>
<td>Design lifetime</td>
<td>60 year</td>
</tr>
<tr>
<td>Input material</td>
<td>U/TRU/RE metal ingot, SFR spent fuel initial and make-up SFR new fuel, waste (ceramic, metal)</td>
</tr>
<tr>
<td>Fuel composition</td>
<td>Fuel composition: U-20.6 wt.%, TRU-10 wt.%</td>
</tr>
<tr>
<td></td>
<td>MA composition: &lt;5 wt.%</td>
</tr>
<tr>
<td></td>
<td>RE composition: &lt;5 wt.%</td>
</tr>
<tr>
<td>Injection</td>
<td>Sodium</td>
</tr>
</tbody>
</table>

The collected uranium and U-TRU ingot are recycled as SFR nuclear fuel after going through the metallic nuclear fuel manufacture process [6].

In addition, in KAPF (Korea Advanced Pyroprocess Facility Plus), uranium metal (U metal, U/TRU metal) produced by treating light-water nuclear reactor (PWR) spent fuel in the pyroprocess is supplied to the SFR nuclear fuel manufacturing facility and used for the initial core and supplement.

2.2. Design Requirement and Criteria. The design standard of SFCF (SFR fuel cycle facility) is shown in Table 1.

2.3. Reference Spent Fuel of SFR. It is assumed that the reference SFR spent fuel is cooled in the storage tank for 5 years or longer after being taken out from the SFR, and the average burnup is 91,429 MWD/tHM. The composition of the major nuclear material before and after the burnup is shown in Table 2.

3. Material Flow of SFR Nuclear Fuel

To calculate the cost of the Pyro-SFR nuclear cycle, the nuclear material balance of each process was calculated. To do this, if we look at the flow of the manufacturing process, the core process of the SFR nuclear fuel manufacture facility is largely divided into the head-end process, the pyroprocess, and the SFR nuclear fuel manufacture process.

The flow of pyroprocess is as shown in Figure 4. The pyroprocess was done in an argon gas atmosphere with little air (≤50 ppm O2).

The SFR nuclear fuel manufacturing facility receives the SFR spent fuel of 32.94 tHM annually based on 200 days...
Figure 1: The sketch of SFR fuel cycle facility.

Figure 2: The mass flow diagram of SFR fuel cycle facility.

Figure 3: The calculation procedures of the manufacturing cost of SFR metallic nuclear fuel.
4. Cost Estimation

4.1. Cost Structure

The cost of investment in facilities is defined as the expense occurring from the time when the work as shown in Table 1 and manufactures SFR metallic nuclear fuel of 38.62 tHM.

Uranium and transuranium (TRU) produced through the pyroprocess is transferred to the nuclear fuel manufacturing hot cell to manufacture the metallic nuclear fuel, and after carrying out the component adjustment (U/TRU/Zr) of the nuclear fuel fuel slug is manufactured using an injection cast method. The completely manufactured fuel slug is charged together with sodium to the fuel rod. A flowchart of the manufacturing process of SFR metallic nuclear fuel is shown in Figure 5.

The assumptions required for the pyroprocess of the SFR nuclear fuel manufacturing facility are shown in Table 3.

The SFR spent fuel is received, and in the SFR nuclear fuel manufacturing facility uranium ingot 21.1 tU/yr and U-TRU-RE ingot 11.75 tHM/yr are produced. In addition, off-gas waste is generated from the high-temperature oxidation volatilization process [8]. This waste will be disposed of in a deep geological repository.
Table 2: Characteristics of reference SFR spent fuel.

<table>
<thead>
<tr>
<th>Nuclides</th>
<th>New fuel</th>
<th>Annual input (g) (600 MWx6)</th>
<th>Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{234}$U</td>
<td>4.19E-02</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>2.05E-02</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>$^{236}$U</td>
<td>1.53E-02</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>$^{237}$U</td>
<td>2.73E+01</td>
<td>70.35</td>
<td></td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>2.72E+01</td>
<td>70.55</td>
<td></td>
</tr>
<tr>
<td>$^{237}$Np</td>
<td>2.57E-01</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>$^{238}$Pu</td>
<td>3.20E-01</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>$^{240}$Pu</td>
<td>4.81E+00</td>
<td>12.46</td>
<td></td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>7.47E-01</td>
<td>1.93</td>
<td></td>
</tr>
<tr>
<td>$^{241}$Pu</td>
<td>7.65E-01</td>
<td>1.98</td>
<td></td>
</tr>
<tr>
<td>Pu</td>
<td>1.01E+01</td>
<td>26.17</td>
<td></td>
</tr>
<tr>
<td>$^{241}$Am</td>
<td>3.89E-01</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>$^{242}$Am</td>
<td>2.17E-02</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>$^{243}$Am</td>
<td>2.95E-01</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>$^{241}$Cm</td>
<td>3.77E-04</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>$^{243}$Cm</td>
<td>1.71E-03</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>$^{244}$Cm</td>
<td>2.00E-01</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>$^{245}$Cm</td>
<td>6.44E-02</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>$^{246}$Cm</td>
<td>3.69E-02</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>MA</td>
<td>1.27E+00</td>
<td>3.28</td>
<td></td>
</tr>
<tr>
<td>TRU</td>
<td>1.14E+01</td>
<td>29.45</td>
<td></td>
</tr>
<tr>
<td><strong>Total (HM)</strong></td>
<td><strong>3.86E+01</strong></td>
<td><strong>Spent fuel</strong></td>
<td><strong>Ratio (%)</strong></td>
</tr>
<tr>
<td>Nuclides</td>
<td>Annual output (g) (600 MWx6)</td>
<td>Ratio (%)</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------------------------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>$^{234}$Am</td>
<td>2.37E-01</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>$^{244}$Am</td>
<td>5.43E-05</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>$^{242}$Cm</td>
<td>2.07E-02</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>$^{243}$Cm</td>
<td>1.90E-03</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>$^{244}$Cm</td>
<td>2.05E-01</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>$^{245}$Cm</td>
<td>6.29E-02</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>$^{246}$Cm</td>
<td>3.67E-02</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>$^{247}$Cm</td>
<td>2.18E-03</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>$^{248}$Cm</td>
<td>1.70E-04</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>MA</td>
<td>9.81E-01</td>
<td>2.98</td>
<td></td>
</tr>
<tr>
<td>TRU</td>
<td>9.13E+00</td>
<td>27.72</td>
<td></td>
</tr>
<tr>
<td><strong>Total (HM)</strong></td>
<td><strong>3.29E+01</strong></td>
<td><strong>Spent fuel</strong></td>
<td><strong>Ratio (%)</strong></td>
</tr>
</tbody>
</table>

Burnup: 91,429 MWd/tHM, cooling: 5 years, calculation code: Origen 2.1, conversion ratio: 0.60.

Table 3: Main constraints of prime process.

<table>
<thead>
<tr>
<th>Category of process</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Head-end cell</strong></td>
<td></td>
</tr>
<tr>
<td>Annual assemblies treated in head-end cell: 930</td>
<td></td>
</tr>
<tr>
<td>Recovery factor of fuel: 99.99%</td>
<td></td>
</tr>
<tr>
<td>Removal rate for Na, Cs, Sr, Ba, I: 99%</td>
<td></td>
</tr>
<tr>
<td><strong>Electrorefining</strong></td>
<td></td>
</tr>
<tr>
<td>Annual throughput: 32.94 tHM</td>
<td></td>
</tr>
<tr>
<td>Throughput per batch: 45.75 kgHM/batch</td>
<td></td>
</tr>
<tr>
<td>Volume of molten salt: 2,900 kg</td>
<td></td>
</tr>
<tr>
<td>LiCl-KCl/batch—1 unit</td>
<td></td>
</tr>
<tr>
<td>Initial UCl$_3$ concentration: 9 wt%</td>
<td></td>
</tr>
<tr>
<td>Recovery factor of uranium in electrorefining: 99.67%</td>
<td></td>
</tr>
<tr>
<td><strong>Electrowinning</strong></td>
<td></td>
</tr>
<tr>
<td>Composition in molten salt: Pu/U &gt; 3</td>
<td></td>
</tr>
<tr>
<td>U coefficient: $U_{salt}/U_{cd} = 1.13$</td>
<td></td>
</tr>
<tr>
<td>Recovery factor of TRU in RAR (residual actinide recovery): 0.99</td>
<td></td>
</tr>
<tr>
<td><strong>Salt waste treatment</strong></td>
<td></td>
</tr>
<tr>
<td>Annual solidification volume of nuclides and concentrated salt: 3,895 kg</td>
<td></td>
</tr>
<tr>
<td>Annual solidification volume of RE/TRU oxide: 870 kg</td>
<td></td>
</tr>
</tbody>
</table>

To estimate the cost, the conversion factor considering the complication, size, and degree of development of the technology was reflected, and the inflation rate was reflected to estimate the construction cost based on the end of 2009. The exchange rate of won-dollar assumed is 1 USD = 1,100 won. The investment costs of the SFR nuclear fuel manufacture facilities are estimated as shown in Table 4.
Table 4: Investment costs of SFR fuel cycle facilities.

<table>
<thead>
<tr>
<th>Capital cost</th>
<th>Estimated cost (kUSD)</th>
<th>Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site preparation</td>
<td>9,445</td>
<td></td>
</tr>
<tr>
<td>Process systems</td>
<td>199,194</td>
<td></td>
</tr>
<tr>
<td>Main processing building</td>
<td>238,668</td>
<td></td>
</tr>
<tr>
<td>Site support facilities</td>
<td>15,266</td>
<td></td>
</tr>
<tr>
<td>Subtotal</td>
<td>462,573</td>
<td>50</td>
</tr>
<tr>
<td>Indirect cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conceptual/final design (14%)</td>
<td>64,760</td>
<td></td>
</tr>
<tr>
<td>Licenses (7%)</td>
<td>32,380</td>
<td></td>
</tr>
<tr>
<td>General and administrative costs (5%)</td>
<td>23,129</td>
<td></td>
</tr>
<tr>
<td>Engineering and construction management (10%)</td>
<td>46,257</td>
<td></td>
</tr>
<tr>
<td>Startup and testing (20%)</td>
<td>92,515</td>
<td></td>
</tr>
<tr>
<td>Initial training (3%)</td>
<td>13,877</td>
<td></td>
</tr>
<tr>
<td>Subtotal</td>
<td>272,918</td>
<td>30</td>
</tr>
<tr>
<td>Contingency (25%)</td>
<td>183,873</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>919,364</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5: Annual operation costs of SFR fuel cycle facilities.

<table>
<thead>
<tr>
<th>Description</th>
<th>Estimated cost (kUSD)</th>
<th>Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O &amp; M cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Staff</td>
<td>18,184</td>
<td>12</td>
</tr>
<tr>
<td>Materials</td>
<td>92,601</td>
<td>62</td>
</tr>
<tr>
<td>Equipment replacement</td>
<td>28,456</td>
<td>19</td>
</tr>
<tr>
<td>Utilities</td>
<td>9,530</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>148,771</td>
<td>100</td>
</tr>
</tbody>
</table>

4.1.2. Operation Cost. The operation cost is defined as all necessary annual expenses related to the use of the facilities and includes the labor cost, maintenance cost, and service costs (water, electricity, etc.).

The estimated annual operation cost of the SFR nuclear fuel manufacturing facilities is shown in Table 5.

4.1.3. Decommissioning Cost. For the decommissioning cost of the SFR nuclear fuel manufacture facilities, it is assumed that 1% of the direct investment cost is accumulated every year for a lifespan period of 60 years in consideration of the scale of the facilities based on expert judgment [9]. Generally, the decommissioning cost of a nuclear facility is calculated to be 10–20% of the direct investment cost. This cost includes the cost of the disposal of equipment. The accumulated annual decommissioning cost is 4,626,000 USD, and the total decommissioning cost is estimated to be 277,544,000 USD.

4.2. Cost Estimation Method. The general cost estimation methods are analogy cost estimation, parametric cost estimation, and engineering cost estimation.

The analogous cost estimation method selects the similar cost object. The parameter cost estimation method assumes the total cost as a dependent variable and sets the characteristics (facility scale, production quantity of nuclear fuel, etc.) of the prime cost as an independent variable. Therefore, the parameter estimation method can be expressed as a regression model.

The engineering cost estimation method carries out a detailed estimation from the low phase, which is a component of the prime cost object and accumulates up to the highest phase to calculate the total cost [10]. Therefore, we need to first conduct a conceptual design for the cost object.

Other cost estimation methods include expert estimations and the earned value management system (EVMS) method. In the expert estimation method, a one-to-one interview with an expert is conducted, or multiple experts are gathered in one place to conduct a group decision making.

The earned value management system (EVMS) method integrates the schedule and cost of the business. Therefore, the EVMS can be classified into plan elements, measurement elements, and analysis elements. The plan elements are the work breakdown structure, control account, and performance measurement baseline, while the measurement elements are composed of the actual cost and earned value. The earned value means the budgeted cost for work performed. In addition, the analysis elements are the scheduled variance, cost variance, and schedule performance index. The purpose of an EVMS is to accurately evaluate the quantitative performance and is a method that can be used to measure the efficiency of the investment cost.

In addition, the levelized unit cost, which is used a lot in the engineering cost estimation method, was used. The levelized unit cost (LUC) can be expressed as in (1) using the continuous discount rate $R$ if it is assumed that the electric power production is continued [11]:

$$
LUC = \frac{PV}{PB} \int_{time} \exp(-Rt) \frac{C_i}{Q_i} dt.
$$

Here LUC is levelized unit cost, PV is present value, PB is present benefits, $C_i$ is costs for the year, $Q_i$ is benefits of the year such as processing volume of uranium or electricity generation, $R = \ln(1 + r)$, and $r$ is discount rate.

4.3. Cash Flow. Figure 6 shows a graph expression of the annual cost trends as overnight costs of investment, O&M, and D&D using (1) based on the end of 2009 on the assumption that the time of initiating the operation of the SFR nuclear fuel manufacturing facilities is 2051, the construction period is 7 years, and the lifespan period is 60 years.

The present cost at the end of the year 2009 needed for the SFR nuclear fuel manufacturing facilities was calculated to be about 531,779 k$, and the present treatment quantity is estimated to be about 96.5 tHM. If the total cost needed for the SFR nuclear fuel manufacturing facilities is subdivided,
it is composed of the investment cost of 138,962 k$ (26%), the operation and maintenance cost of 380,971 k$ (72%), and the decontamination and decommissioning cost of 11,845 k$ (2%). These three main costs (investment cost, O&M cost, and D&D cost) were discounted by 5% using (2) with the annual cost from 2044 to 2110 as shown in Figure 6:

\[
NPV = \sum_{t} \frac{AC(t)}{(1+r)^{Y_t-Y_b}}. \tag{2}
\]

Here NPV is net present value, AC is annual cost, r is discount rate, Y_t is current year, and Y_b is base year.

As the result of dividing the total present value of the SFR nuclear fuel manufacturing facilities by the total present treatment quantity as a benefit, the levelized unit cost (LUC) for SFR nuclear fuel manufacturing facilities was calculated to be 5,311 $/kgHM.

5. The Break-Even Point Analysis

Generally, the break-even point is the point where total revenue equals total cost (i.e., the point of zero profit). Therefore, in this paper, only the SFR nuclear fuel manufacture cost is changed, and fixed values for all other costs were used to define the SFR nuclear fuel manufacturing cost in which the direct disposal is equal to the Pyro-SFR nuclear fuel cycle cost as the break-even point, as in (3) [12].

The direct disposal is considered applicable to vertical disposal in 500 m underground granitic rocks. The objects of disposal cost are limited to the deep geological repository with disposal capacity covering PWR spent fuel (20,000 tons) on the assumption that the PWRs initial enrichment is 4.5% and its burnup is 55 GWD/MtU. In addition, the cooling time is assumed to last for 10 years [13]:

\[
BEP_{SFR \text{ Fuel Manufacturing}} = TC_D - (MC + CC + EC + ISC + RC_{Pyro} + DC_{Pyro \text{ Waste}}) = 0. \tag{3}
\]

Here \(BEP_{SFR \text{ Fuel Manufacturing}}\) is a break-even point of the manufacturing cost of metallic SFR fuel for the direct disposal option, \(TC_D\) is the total cost of direct disposal option, MC is the raw material cost, CC is the conversion cost, EC is the enrichment cost, ISC is the interim storage cost, RC_{Pyro} is the pyroprocess cost, and DC_{Pyro Waste} is the disposal cost of the pyrowaste.

Additionally, if the break-even point is expressed in cost accounting, it could be expressed as [14]

\[
BEP_{\text{Accounting}} = \frac{FC}{UCM}. \tag{4}
\]

Here FC is the fixed cost and UCM is the unit contribution margin.

In (4), the fixed cost is the investment cost of the SFR nuclear fuel manufacturing facilities, and the unit contribution margin is the value calculated by dividing the value of the subtraction of the variable cost from the total revenue by the output [14]:

\[
UCM = \frac{TR - VC}{Q}. \tag{5}
\]

Here TR is the total revenue, VC is the variable cost, and Q is the output.

In (5), the total revenue can be calculated as the fuel sales, and the variable cost can use the operation cost change.
Table 6: Input data for economic assessment of SFR fuel.

<table>
<thead>
<tr>
<th>Category</th>
<th>Unit</th>
<th>Reference</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium</td>
<td>$/kgU</td>
<td>150</td>
<td>53</td>
<td>318</td>
</tr>
<tr>
<td>Conversion*</td>
<td>$/kgU</td>
<td>6</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Enrichment*</td>
<td>$/SWU</td>
<td>165</td>
<td>84</td>
<td>210</td>
</tr>
<tr>
<td>Reprocessing cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UO₂ pyroprocess (reduction/refining)</td>
<td>$/kgHM</td>
<td>781</td>
<td>373</td>
<td>1,866</td>
</tr>
<tr>
<td>SFR metal fuel pyroprocess</td>
<td>$/kgHM</td>
<td>2,000</td>
<td>1,000</td>
<td>2,500</td>
</tr>
<tr>
<td>Fabrication cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UO₂ fuel*</td>
<td>$/kgHM</td>
<td>256</td>
<td>206</td>
<td>307</td>
</tr>
<tr>
<td>SFR metal fuel</td>
<td>$/kgHM</td>
<td>3,000</td>
<td>1,000</td>
<td>4,000</td>
</tr>
<tr>
<td>Storage cost*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UO₂ S/F dry storage</td>
<td>$/kgHM</td>
<td>180</td>
<td>78</td>
<td>392</td>
</tr>
<tr>
<td>UO₂ pyroprocess, HLW dry storage</td>
<td>$/m³</td>
<td>120,000</td>
<td>80,000</td>
<td>200,000</td>
</tr>
<tr>
<td>SFR pyroprocess, HLW dry storage</td>
<td>$/m³</td>
<td>120,000</td>
<td>80,000</td>
<td>200,000</td>
</tr>
<tr>
<td>Disposal cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LILW (long lived)*</td>
<td>$/m³</td>
<td>6,000</td>
<td>4,000</td>
<td>8,000</td>
</tr>
<tr>
<td>Packing (PWR SF)*</td>
<td>$/kgHM</td>
<td>350</td>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td>HLW (underground cost)</td>
<td>$/m³</td>
<td>1,200</td>
<td>600</td>
<td>2,000</td>
</tr>
</tbody>
</table>

*OECD/NEA, advanced nuclear fuel cycles and radioactive waste management, 2006 [7].

5.1 Input Data. The input data used to calculate the nuclear cycle cost can be largely divided into the economic data and technical data. In particular, the unit cost should be adjusted to the cost at which the inflation index is reflected in case a constant price is not used. Namely, it is necessary to calculate the cost fitting for a certain standard year. The input data is shown in Table 6. In addition, it is assumed that the cost of construction of the SFR is about 20% higher than that of light-water reactor [7].

5.2 The Break-Even Point Calculation Result. As a result of calculating the cost of the nuclear fuel cycle using the reference value in Table 6, the direct disposal cost was calculated to be 6.71 mills/kWh, and the Pyro-SFR fuel cycle cost was calculated to be 6.60 mills/kWh using (1).

In addition, as a result of calculating the break-even point of the manufacture cost of SFR metallic nuclear fuel for direct disposal, 6.71 mills/kWh was obtained. However, Pyro-SFR was calculated to be 6.60 mills/kWh using (1). The method of calculating the break-even point is shown in Figure 7. The Pyro-SFR nuclear fuel cycle cost was calculated to be 6.60 mills/kWh using (1). In addition, as a result of calculating the break-even point of the manufacture cost of SFR metallic nuclear fuel for direct disposal, 6.71 mills/kWh was obtained. However, Pyro-SFR was calculated to be 6.60 mills/kWh using (1). The method of calculating the break-even point is shown in Figure 7. The Pyro-SFR nuclear fuel cycle cost was calculated to be 6.60 mills/kWh using (1).
disposal using the equations in Table 7, the break-even point was calculated to be $5,267/kgHM, as shown in Figure 7.

Therefore, the pyroprocess cost and the SFR metallic nuclear fuel manufacture cost, $5,272/kgHM, exceeds the break-even point of $5,267/kgHM slightly. Here, an inflation rate of 2.3% is applied because the inflation rate was specified as 2.3% in the Korea Radioactive Waste Management Law [16].

In addition, the cost difference between the break-even point and estimated cost of SFCF is within the relevant range of the uncertainty level of Class 3 in accordance with the general cost estimate classification matrix of AACE (the Association for the Advancement of Cost Engineering). It is expected that the calculated break-even point will be used as a valuable clue for estimating the economic feasibility of the SFR metallic nuclear fuel in the future.

6. Conclusions

The break-even point of the manufacturing cost of the SFR nuclear fuel using the nuclear fuel cycle cost was calculated to be $5,267/kgHM. Namely, if the manufacturing cost of SFR metallic nuclear fuel including the pyroprocess cost is less than $5,267/kgHM, we can say that the economic feasibility of the SFR metallic nuclear fuel in the Pyro-SFR nuclear cycle exists. In other words, if the SFCF cost excluding the pyroprocess cost of $2,000/kgHM announced in the report of the OECD/NEA in 2006 is less than $3,267, it can be judged that the economic feasibility of SFR metallic nuclear fuel exists.

In this paper, the investment cost of the manufacturing facilities of SFR nuclear fuel was estimated to be about $919 MUSD, the annual operation cost was about $149 MUSD,
and the decontamination and decommissioning cost was about 5 MUSD based on the price at the end of 2009. In addition, the levelized unit cost of the manufacturing of SFR metallic nuclear fuel including the pyroprocess cost was calculated to be 5,311 $/kgHM, and it exceeded the break-even point $5,267/kgHM. Therefore, based on the manufacturing cost of the metallic nuclear fuel the cost difference between the break-even point and the estimated cost of SFC is not only small but also within the relevant range of the uncertainty level of Class 3 AACE estimate.

Manufacturing facilities of SFR nuclear fuel are presently in the stage of research and development, and no commercial scale processing equipment and facilities exist.

To reduce this uncertainty, therefore, is difficult to judge the economic feasibility. However, if the technology developments of a mass production pyroprocess system and SFR metallic nuclear fuel manufacturing facilities are enhanced, the economics of SFR metallic nuclear fuel are expected to be better.

Acknowledgment

This work was supported financially by the Ministry of Education, Science and Technology under the Mid- and Long-Term Nuclear R & D Project, and the authors express their sincere gratitude for supporting this important work.

References

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