Hindawi Publishing Corporation
Science and Technology of Nuclear Installations
Volume 2013, Article ID 412349, 10 pages
http://dx.doi.org/10.1155/2013/412349

Research Article

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

S. K. Kim,[1] W. I. Ko,[1] and Yoon Hee Lee[2]

[1] *Korea Atomic Energy Research Institute, 1045 Daedeokdaero, Yuseung-Gu, Daejeon 305-353, Republic of Korea*
[2] *Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 291 Daehakro, Yuseong-Gu, Daejeon 305-353, Republic of Korea*

Correspondence should be addressed to S. K. Kim; sgkim1@kaeri.re.kr

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

Academic Editor: Michael F. Simpson

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 has 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 a 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 manufacture 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.

2.1. Major Function of SFR Fuel Cycle Facility (SFCF). The SFR fuel cycle facility (SFCF) recycles the spent fuel discharged from the SFR of 6 units of a 600 MWe as shown Figure 2.

In the main manufacture facility, after going through the head-end processes such as inspection, dissolution, cutting, and removing sodium of the spent fuel, uranium is collected through the electrorefining process [4], and by collecting the remaining uranium and TRU (transuranium) through the electrowinning process [5].

Table 1: Design standard of SFR fuel cycle facilities.

Capacity	
Annual SFR SF	32.94 tHM/yr (9.12 tTRU/yr); SF of SFR 6 unit (600 MWe per unit)
Manufacturing of SFR new fuel	HM: 38.62 tHM/yr, TRU: 11.4 tTRU/yr, annual manufacturing of fuel rod: 327,139/yr, annual fuel assemblies: 1,207/yr
Plant function	Head-end process, pyroprocess, manufacturing of SFR nuclear fuel
Annual load factor	55%, 200 day/year
Design lifetime	60 year
Input material	U/TRU/RE metal ingot, SFR spent fuel
Output material	initial and make-up SFR new fuel, waste (ceramic, metal)
Fuel composition	
Fuel composition	U-20.6 wt.%, TRU-10 wt.%
MA composition	<5 wt.%
RE composition	<5 wt.%
Injection	Sodium

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 O_2).

The SFR nuclear fuel manufacturing facility receives the SFR spent fuel of 32.94 tHM annually based on 200 days

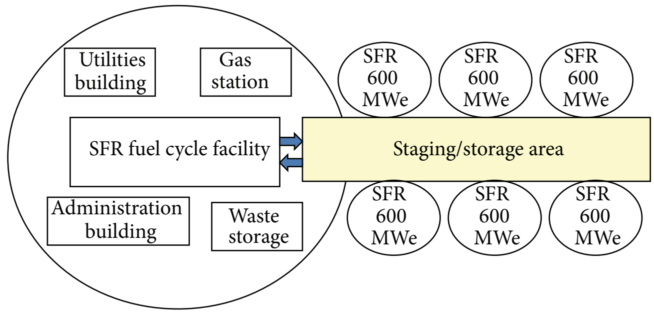


Figure 1: The sketch of SFR fuel cycle facility.

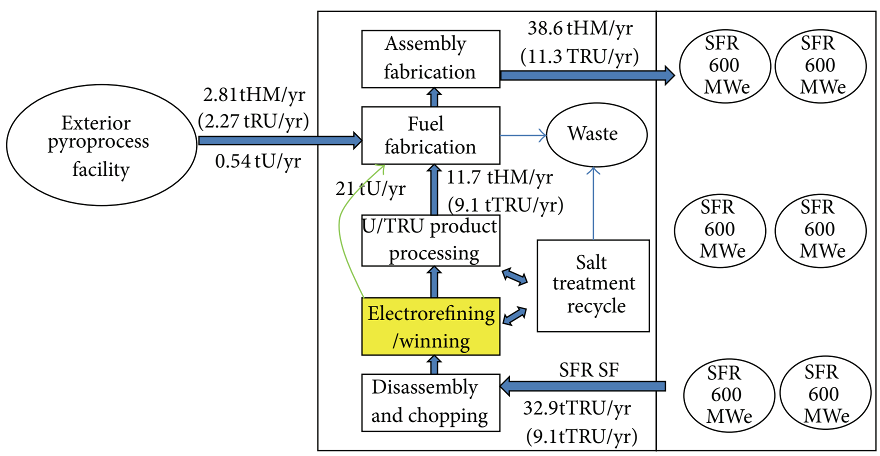


Figure 2: The mass flow diagram of SFR fuel cycle facility.

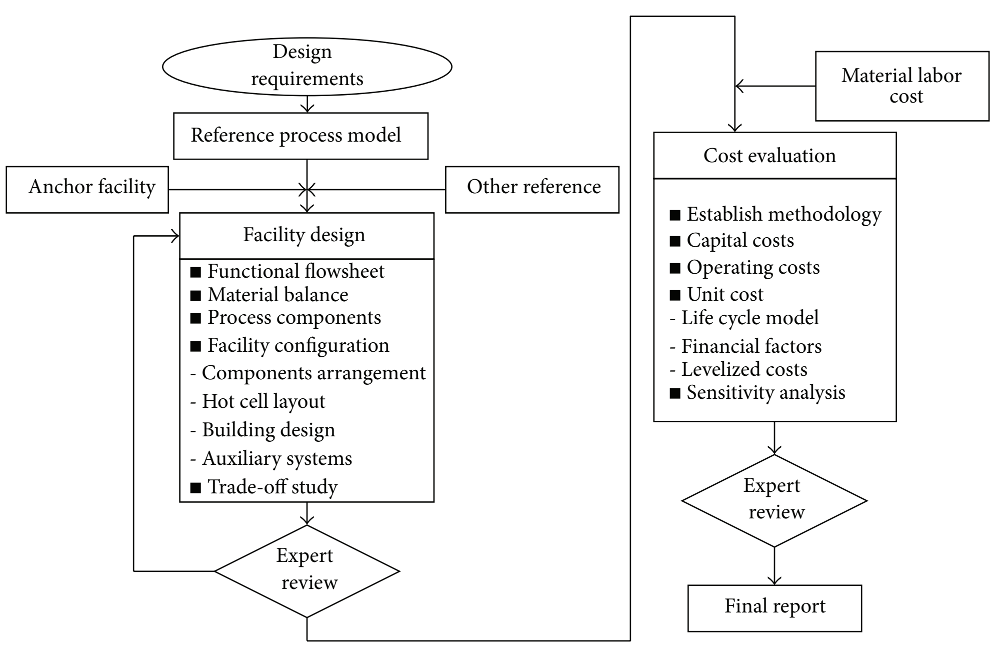


Figure 3: The calculation procedures of the manufacturing cost of SFR metallic nuclear fuel.

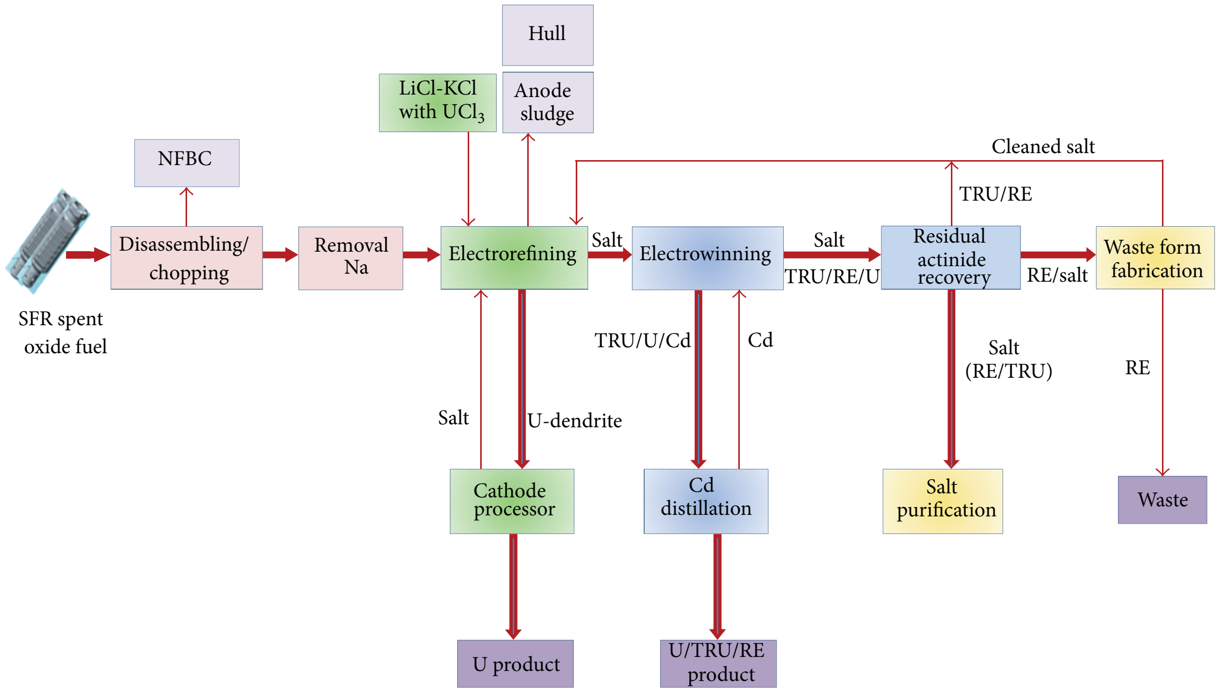


Figure 4: The process flow diagram of pyroprocess.

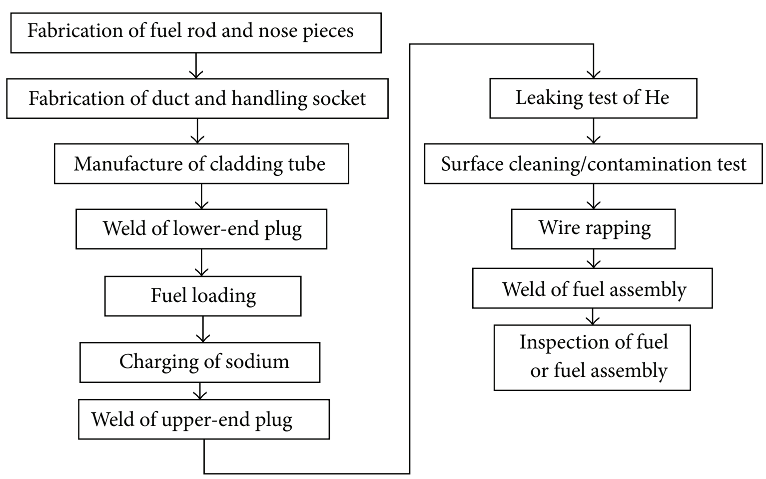


Figure 5: The manufacturing process of SFR nuclear fuel.

of 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.

4. Cost Estimation

4.1. Cost Structure

4.1.1. Investment Cost. The cost of investment in facilities is defined as the expense occurring from the time when the

Table 2: Characteristics of reference SFR spent fuel.

Nuclides	New fuel Annual input (g) (600 MW × 6)	Ratio (%)
^{234}U	4.19E − 02	0.11
^{235}U	2.05E − 02	0.05
^{236}U	1.53E − 02	0.04
^{238}U	2.73E + 01	70.35
U	2.72E + 01	70.55
^{237}Np	2.57E − 01	0.67
^{238}Pu	3.20E − 01	0.83
^{239}Pu	4.81E + 00	12.46
^{240}Pu	3.46E + 00	8.97
^{241}Pu	7.47E − 01	1.93
^{242}Pu	7.65E − 01	1.98
Pu	1.01E + 01	26.17
^{241}Am	3.89E − 01	1.01
^{242}Am	2.17E − 02	0.06
^{243}Am	2.95E − 01	0.76
^{242}Cm	3.77E − 04	0.00
^{243}Cm	1.71E − 03	0.00
^{244}Cm	2.00E − 01	0.52
^{245}Cm	6.44E − 02	0.17
^{246}Cm	3.69E − 02	0.10
MA	1.27E + 00	3.28
TRU	1.14E + 01	29.45
Total (HM)	3.862E + 01	
Nuclides	Spent fuel Annual output (g) (600 MW × 6)	Ratio (%)
^{234}U	3.72E − 02	0.11
^{235}U	1.04E − 02	0.04
^{236}U	1.68E − 02	0.05
^{237}U	1.10E − 04	0.00
^{238}U	2.37E + 01	72.07
^{239}U	4.00E − 05	0.00
U	23.809	72.3
^{237}Np	1.36E − 01	0.41
^{238}Np	1.53E − 04	0.00
^{239}Np	5.76E − 03	0.02
^{238}Pu	3.09E − 01	0.92
^{239}Pu	3.66E + 00	11.10
^{240}Pu	3.00E + 00	9.09
^{241}Pu	5.05E − 01	1.53
^{242}Pu	6.84E − 01	2.08
Pu	8.15E + 00	24.72
^{241}Am	2.69E − 01	0.82
^{242M}Am	3.25E − 03	0.01
^{242}Am	1.06E − 04	0.00

Table 2: Continued.

Nuclides	Spent fuel Annual output (g) (600 MW × 6)	Ratio (%)
^{243}Am	2.37E − 01	0.72
^{244}Am	5.43E − 05	0.00
^{242}Cm	2.07E − 02	0.06
^{243}Cm	1.90E − 03	0.01
^{244}Cm	2.05E − 01	0.62
^{245}Cm	6.29E − 02	0.19
^{246}Cm	3.67E − 02	0.11
^{247}Cm	2.18E − 03	0.01
^{248}Cm	1.70E − 04	0.00
MA	9.81E − 01	2.98
TRU	9.13E + 00	27.72
Total (HM)	3.294E + 01	

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

Table 3: Main constraints of prime process.

Category of process	Assumption
Head-end cell	Annual assemblies treated in head-end cell: 930
	Recovery factor of fuel: 99.99%
	Removal rate for Na, Cs, Sr, Ba, I: 99%
Electrorefining	Annual throughput: 32.94 tHM
	Throughput per batch: 45.75 kgHM/batch
	Volume of molten salt: 2,900 kg LiCl-KCl/batch—1unit
	Initial UCl_3 concentration: 9 wt%
	Recovery factor of uranium in electrorefining: 99.67%
Electrowinning	Composition in molten salt: Pu/U > 3
	U coefficient: U_{salt}/U_{cd} = 1.13
	Recovery factor of TRU in RAR (residual actinide recovery): 0.99
Salt waste treatment	Annual solidification volume of nuclides and concentrated salt: 3,895 kg
	Annual solidification volume of RE/TRU oxide: 870 kg

owner decides on the construction of the facilities to the time when the facilities are commercially operated, which includes the costs of obtaining the land, the design, the infrastructure, the construction, the equipment, and the interest accrual during the construction period.

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.

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

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.

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

Description	Estimated cost (kUSD)	Ratio (%)
O & M cost		
Staff	18,184	12
Materials	92,601	62
Equipment replacement	28,456	19
Utilities	9,530	7
Total	148,771	100

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.

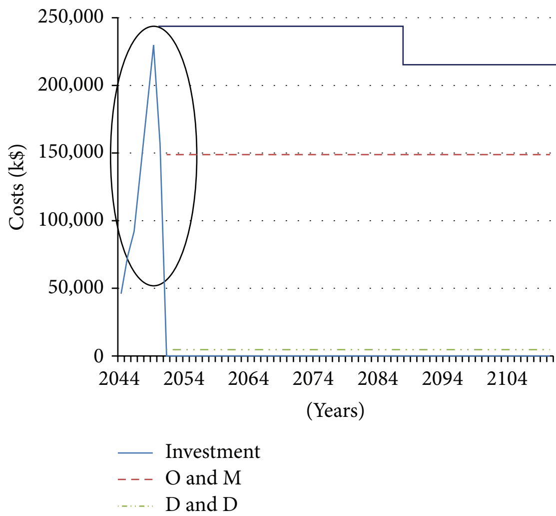
In addition, the levelized unit cost, which is used a lot in the engineering cost estimation method, was used. The levelized unit cost (LUC) can be expressed as in (1) using the continuous discount rate R if it is assumed that the electric power production is continued [11]:

$$\mathrm{LUC} = \frac{\mathrm{PV}}{\mathrm{PB}} \frac{\int_{\mathrm{time}} \exp(-Rt)\, C_i dt}{\int_{\mathrm{time}} \exp(-Rt)\, Q_i dt}. \quad (1)$$

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 manufacture 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,



Years	Costs (k$)		
	Investment	O and M	D and D
2044	45,968		
2045	73,549		
2046	91,936		
2047	137,905		
2048	183,873		
2049	229,841		
2050	156,292		
2051	0	148,771	4,626
2052	"	"	"
∫	∫	∫	∫
2110	0	148,771	4,626
Total	919,364	8,926,282	277,544

FIGURE 6: Cost trends of SFR facilities.

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:

$$\mathrm{NPV} = \sum_{t} \frac{\mathrm{AC}(t)}{(1+r)^{Y_c - Y_b}}. \tag{2}$$

Here NPV is net present value, AC is annual cost, r is discount rate, Y_c 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 PWR's 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]:

$$\begin{aligned} &\mathrm{BEP}_{\text{SFR Fuel Manufacturing}} \\ &\quad = \mathrm{TC}_D - \left(\mathrm{MC} + \mathrm{CC} + \mathrm{EC} + \mathrm{ISC} + \mathrm{RC}_{\text{Pyro}} + \mathrm{DC}_{\text{Pyro Waste}}\right) \\ &\quad = 0. \end{aligned} \tag{3}$$

Here $\mathrm{BEP}_{\text{SFR Fuel Manufacturing}}$ is a breakeven 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, $\mathrm{RC}_{\text{Pyro}}$ is the pyroprocess cost, and $\mathrm{DC}_{\text{Pyro Waste}}$ is the disposal cost of the pyrowaste.

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

$$\mathrm{BEP}_{\text{Accounting}} = \frac{\mathrm{FC}}{\mathrm{UCM}}. \tag{4}$$

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]:

$$\mathrm{UCM} = \frac{\mathrm{TR} - \mathrm{VC}}{\mathrm{Q}}. \tag{5}$$

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.

Category	Unit	Reference	Minimum	Maximum
Uranium	\$/kgU	150	53	318
Conversion*	\$/kgU	6	3	9
Enrichment*	\$/SWU	165	84	210
Reprocessing cost				
UO_2 pyroprocess (reduction/refining)	\$/kgHM	781	373	1,866
SFR metal fuel pyroprocess	\$/kgHM	2,000	1,000	2,500
Fabrication cost				
UO_2 fuel*	\$/kgHM	256	206	307
SFR metal fuel	\$/kgHM	3,000	1,000	4,000
Storage cost*				
UO_2 S/F dry storage	\$/kgHM	180	78	392
UO_2 pyroprocess, HLW dry storage	\$/m^3	120,000	80,000	200,000
SFR pyroprocess, HLW dry storage	\$/m^3	120,000	80,000	200,000
Disposal cost				
LILW (long lived)*	\$/m^3	6,000	4,000	8,000
Packing (PWR SF)*	\$/kgHM	350	250	500
HLW (underground cost)	\$/m^3	1,200	600	2,000

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

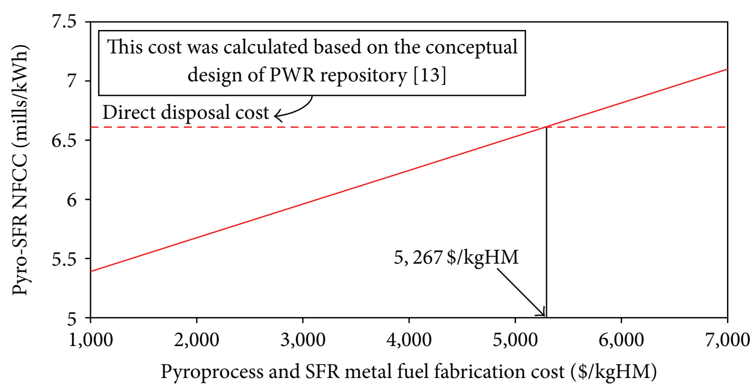


Figure 7: The break-even point of the manufacturing cost of SFR metallic nuclear fuel.

according to the output of the nuclear fuel of the SFR nuclear fuel manufacturing facilities. The output can also use the quantity of manufacturing of SFR nuclear fuel. Therefore, the break-even point obtained with the method of accounting means the quantity of the manufacturing of the SFR nuclear fuel, which makes the revenue equal to the cost. However, in this paper, through an analysis of the comparative cost of the direct disposal and Pyro-SFR nuclear fuel cycle, as in (3), rather than using the method of cost accounting, the break-even point of the SFR nuclear fuel manufacture cost was calculated. This is because the method of calculating the break-even point in the accounting method should use the past actual cost to make the reliability of the cost calculation results. Therefore, calculating the break-even point using the engineering cost estimation method, which uses the nuclear fuel cycle cost, can be regarded as a valid method whose accuracy is somewhat higher [15].

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

Table 7: Equations for the direct disposal cost.

Recharge interval	$R_i = \dfrac{C_s}{N_b} \times \dfrac{\mathrm{BU}}{\mathrm{MWt} \times C_f \times 365}$ (Unit: year)
Generation cost	$C = F_c + V_c = \dfrac{C_{\mathrm{uc}} \cdot R}{T \cdot U_r \cdot (1 - I_c)} + \mathrm{NFCC}$
Quantity of fabrication	$\mathrm{Qf}(t) = \dfrac{C_s}{N_b},\ t = \text{batch}$
Quantity of enrichment	$\mathrm{Qe}(t) = \left[V(\mathrm{EL}) + \left(\dfrac{\mathrm{EL} - T_a}{\mathrm{NAT} - T_a} - 1\right) \cdot V(T_a) - \dfrac{\mathrm{EL} - T_a}{\mathrm{NAT} - T_a} V(\mathrm{NAT})\right] \mathrm{Qf}(t)(1 + \mathrm{LF})$
Quantity of conversion	$\mathrm{Qc}(t) = \dfrac{\mathrm{EL} - T_a}{\mathrm{NAT} - T_a} \mathrm{Qf}(t)(1 + \mathrm{LF})$
Quantity of uranium	$\mathrm{Qu}(t) = \mathrm{Qc}(t)(1 + \mathrm{LF})$
Spent fuel generation	$\mathrm{Qsf}(t) = \dfrac{P365C_f}{\varepsilon \mathrm{BU}}$
Cost of uranium	$\mathrm{Cu} = \sum_t \dfrac{\mathrm{Qu}(t) \cdot \mathrm{UCu} \cdot (1 + E_{\mathrm{U}})^{L(t) - \mathrm{LEDu} - \mathrm{YRc}}}{(1 + D)^{L(t) - \mathrm{LEDu} - \mathrm{YRp}}}$
Cost of conversion	$\mathrm{Cc} = \sum_t \dfrac{\mathrm{Qc}(t) \cdot \mathrm{UCc} \cdot (1 + E_c)^{L(t) - \mathrm{LEDc} - \mathrm{YRc}}}{(1 + D)^{L(t) - \mathrm{LEDc} - \mathrm{YRp}}}$
Cost of enrichment	$\mathrm{Ce} = \sum_t \dfrac{\mathrm{Qe}(t) \cdot \mathrm{UCe} \cdot (1 + E_e)^{L(t) - \mathrm{LEDe} - \mathrm{YRc}}}{(1 + D)^{L(t) - \mathrm{LEDe} - \mathrm{YRp}}}$
Cost of fabrication	$\mathrm{Cf} = \sum_t \dfrac{\mathrm{Qf}(t) \cdot \mathrm{UCf} \cdot (1 + E_f)^{L(t) - \mathrm{LEDf} - \mathrm{YRc}}}{(1 + D)^{L(t) - \mathrm{LEDf} - \mathrm{YRp}}}$
Cost of transportation; applied LAG time	$\mathrm{Ct} = \sum_t \dfrac{\mathrm{Qsf}(t) \cdot \mathrm{UCt} \cdot (1 + E_t)^{D(t) + \mathrm{LAGt} - \mathrm{YRc}}}{(1 + D)^{D(t) + \mathrm{LAGt} - \mathrm{YRp}}}$
Cost of storage	$\mathrm{Cs} = \sum_t \dfrac{\mathrm{Qsf}(t) \cdot \mathrm{UCs} \cdot (1 + E_s)^{D(t) + \mathrm{LAGs} - \mathrm{YRc}}}{(1 + D)^{D(t) + \mathrm{LAGs} - \mathrm{YRp}}}$
Cost of disposal	$\mathrm{Cd} = \sum_t \dfrac{\mathrm{Qsf}(t) \cdot \mathrm{UCd} \cdot (1 + E_d)^{D(t) + \mathrm{LAGd} - \mathrm{YRc}}}{(1 + D)^{D(t) + \mathrm{LAGd} - \mathrm{YRp}}}$
Total cost of direct disposal option	$\mathrm{TC}_D = \mathrm{Cu}(t) + \mathrm{Cc}(t) + \mathrm{Ce}(t) + \mathrm{Cf}(t) + \mathrm{Ct}(t) + \mathrm{Cs}(t) + \mathrm{Cd}(t)$

R_i: recharge interval, C_s: core size, N_b: total number of batches, BU: burn up, MWt: thermal power, C_f: load (Capacity) factor, $L(t)$: loading time, $D(t)$: discharging time, LED: lead times, LAG: lag times, F_c: fixed unit cost, V_c: variable unit cost, C_{uc}: construction unit cost (\$/kW), R: fixed charge rate, T: 8760 (=365 days × 24 hours), I_c: consumption rate in power plant, NFCC: nuclear fuel cycle cost, EL: enrichment of equilibrium core, NAT: enrichment of natural uranium, T_a: tail assay, LF: loss rate factor, $V(x) = (2x-1)\ln(x/(1-x))$, Cu: cost of uranium, Qu(t): quantity of uranium, P: capacity (MWe), ε: thermodynamic efficiency (MWe/MWt), UC: unit cost, UCu: unit cost of uranium, Eu: escalation rate of uranium, D: discount rate, YRt: base year, Qsf(t): quantity of spent fuel, $\mathrm{TC}_D(t)$: total cost of direct disposal option, Cu(t): uranium cost, Cc(t): conversion cost, Ce(t): enrichment cost, Cf(t): fabrication cost, Ct(t): transportation cost, Cs(t): storage cost, Cd(t): disposal cost, t: years.

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 SFCF 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

[1] D. C. Wade and R. N. Hill, "The design rationale of the IFR," *Progress in Nuclear Energy*, vol. 31, no. 1-2, pp. 13–42, 1997.

[2] H. Ohmura, K. Mizuguchi, S. Kanamura et al., "Development of hybrid reprocessing technology based on solvent extraction and pyro-chemical electrolysis," *Progress in Nuclear Energy*, vol. 53, pp. 940–943, 2011.

[3] K. sungjin, *The Theory of Cost Estimation*, Dunam Press, Seoul, Republic of Korea, 2010.

[4] J. J. Laidler, L. Burris, E. D. Collins et al., "Chemical partitioning technologies for an ATW system," *Progress in Nuclear Energy*, vol. 38, no. 1-2, pp. 65–79, 2001.

[5] KAERI, "Development of Head-end Pyrochemical Reduction Process for Advanced Oxide Fuels," KAERI/RR-2939, 2007.

[6] C. E. Boardman, M. Thompson, C. E. Walter, and C. S. Ehrman, "The separations technology and transmutation systems (STATS) report -implications for nuclear power growth and energy sufficiency," *Progress in Nuclear Energy*, vol. 32, no. 3-4, pp. 411–419, 1998.

[7] OECD/NEA, *Advanced Nuclear Fuel Cycles and Radioactive Waste Management*, OECD Publishing, 2006, Appendix L.

[8] C. E. Till, Y. I. Chang, and W. H. Hannum, "The integral fast reactor-an overview," *Progress in Nuclear Energy*, vol. 31, no. 1-2, pp. 3–11, 1997.

[9] KAERI, "Preliminary Conceptual Design and Cost Estimation for SFR fuel cycle facility," KAERI/CM-1383, 2010.

[10] D. E. Shropshire, K. A. Williams, W. B. Boore et al., *Advanced Fuel Cycle Cost Basis*, Idaho National Laboratory, Idaho Falls, Idaho, USA, 2008.

[11] OECD/NEA, "The Economics of the Nuclear Fuel Cycle," Tech. Rep. NEA/EFC/DOC(93), 1993.

[12] KAERI, "Development of System Engineering Technology for Nuclear Fuel Cycle," KAERI/RR-3426, 2011.

[13] KAERI, "KAERI's spent fuel repository design evaluation and cost estimation," R&D Report 2003-02, 2003.

[14] M. Maryanne Mowen, R. don Hansen, and L. dan Heitger, *Managerial Accounting*, South-Western Press, 4th edition, 2012.

[15] S. K. Kim, W. I. Ko, H. D. Kim, S. T. Revankar, W. Zhou, and D. Jo, "Cost-benefit analysis of BeO-UO_2 nuclear fuel," *Progress in Nuclear Energy*, vol. 52, no. 8, pp. 813–821, 2010.

[16] "Ministry of Knowledge Economy," Radioactive Waste Management Law, Article 15, Section 1, 2009.