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Advanced Depreciation Cost Analysis for a Commercial Pyroprocess Facility in Korea

Sungki Kim [a], Wonil Ko [a], Saerom Youn [b], Ruxing Gao [b], Yanghon Chung [c], and Sungsig Bang [c,*]

[a] Korea Atomic Energy Research Institute, 1045 Daedeokdaero, Yuseong-gu, Daejeon 305-353, South Korea
[b] University of Science and Technology, 217 Gajungro, Yuseong-gu, Daejeon, 305-350, South Korea
[c] Korea Advanced Institute of Science and Technology, Department of Business and Technology Management, 291 Deahak-ro, Yuseong-gu, Daejeon 305-701, South Korea

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ABSTRACT

The purpose of this study is to present a rational depreciation method for a pyroprocess cost calculation. Toward this end, the so-called advanced decelerated depreciation method (ADDM) was developed that complements the limitations of the existing depreciation methods such as the straight-line method and fixed percentage of declining-balance method. ADDM was used to show the trend of the direct material cost and direct labor cost compared to the straight-line or fixed percentage of the declining-balance methods that are often used today. As a result, it was demonstrated that the depreciation cost of the ADDM, which assumed a pyroprocess facility's life period to be 40 years with a deceleration rate of 5%, takes up 4.14% and 27.74% of the pyroprocess unit cost ($781/kg heavy metal) in the 1st and final years, respectively. In other words, it was found that the ADDM can cost the pyroprocess facility's capital investment rationally every year. Finally, ADDM's validity was verified by confirming that the sum of the depreciation cost by year, and the sum of the purchasing cost of the building and equipment, are the same.

1. Introduction

Although Korea operates a total of 24 units of nuclear power plants today, it is expected that the temporary storage facility for the spent fuel will be saturated incrementally starting from 2024 [1], and the spent fuel management issue is emerging as an important issue. Accordingly, Korea is paying utmost attention to pyroprocess technology development in order to reduce its spent fuel inventory [2,3]. Currently, KAERI (Korea Atomic Energy Research Institute) operates the engineering-scale PRIDE (PyRoprocess Integrated inactive DEmonstration facility). In 2011, the conceptual design of the Korea Advanced

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* Corresponding author.
E-mail address: ssbang@kaist.ac.kr (S. Bang).

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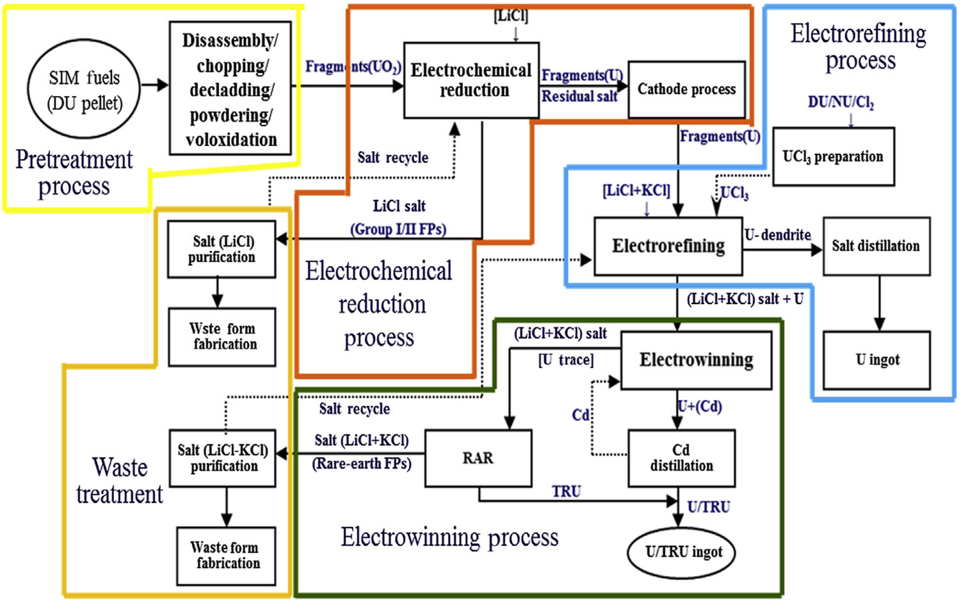

Fig. 1 – Diagram of the pyroprocess.

Pyroprocess Facility Plus (KAPF+) was completed [3]. Fig. 1 is a diagram of the pyroprocess. KAPF+'s capacity is shown in Table 1, and specifications and key process equipment for the pyroprocess facilities are shown in Tables 2 and 3. The pyroprocess produces uranium/transurarium (U/TRU) metal ingots using four important processes—pretreatment, electrochemical reduction, electrorefining, and electrowinning—in order to recycle spent fuel. Table 4 shows the cost that is injected into the KAPF+.

A U/TRU ingot produced at the pyroprocess facility is used as a sodium-cooled fast reactor (SFR) nuclear fuel's raw material. Thus, the pyroprocess is considered as a future nuclear power technology that can reduce the spent fuel inventory considerably [3,4].

Elements that affect the cost include direct material costs, direct labor costs, and expenses [5,6]. High-priced raw materials that are injected during the pyroprocess include: platinum; anode electrodes, needed during the electrochemical reduction process; and Li_3PO_4, used during the salt purification process [3,4]. Moreover, the unit cost of the direct material cost and direct labor cost changes depending on the market transaction price. Manufacturing indirect cost is included in the operation and maintenance cost in Table 4, and includes the building or facility's depreciation cost, plant maintenance cost, insurance premium, tax, cost of consumables, and salary for facility supervisors [6–8]. Accordingly, indirect costs of manufacturing include the costs incurred during the manufacturing period, and are allocated artificially to the pyroprocess-manufactured product.

The input of pyroprocess unit cost data is essential for calculating the pyroprocess-SFR nuclear fuel cycle cost. Moreover, since the pyroprocess facility's depreciation cost is included in the manufacturing indirect cost of the pyroprocess cost, it can become an important element for judging economic viability of the pyroprocess [9].

According to the results of the engineering cost estimation based on conceptual design, the overnight cost of capital investment that is invested in the pyroprocess facility's building and equipment was calculated at 12.3% of the pyroprocess costs [\$781/kg heavy metal (HM), reference year = 2009] [10–12]. The engineering cost estimation method calculates the pyroprocess unit cost by assuming that the capital investment is injected in the beginning over a number of years without costing it annually. The capital cost is invested during the initial stage of the pyroprocess facility construction in order to calculate the pyroprocess unit cost. Accordingly, when the pyroprocess facility's life period span is long, the uncertainty of the pyroprocess unit's cost increases as it is not possible to suitably factor in yearly capital investment during the facility's life period.

Since the pyroprocess unit cost is calculated by taking the sum of the costs that are incurred each year, divided by the total amount of U/TRU ingot produced, the pyroprocess unit cost uncertainty increases when the uncertainty of the costs incurred each year increases. An accounting method is needed that can decrease the uncertainty of the capital investment that is injected into the pyroprocess facility every year of the facility's life, in order that the unit cost can be factored in. The straight-line method and the fixed percentage of declining-balance method are depreciation methods that are used most often in order to cost the capital investment annually. However, these methods are rational when the facility and

Table 1 – The capacity of Korea Advanced Pyroprocess Facility Plus.

Classification	Criteria
Capacity	Pretreatment: Spent fuel of 400 tHM/y Temporary storage: 400 tHM/y Pyroprocessing: 200 tHM/y/module × 2 module

tHM, tons of heavy metal.

Table 2 – The major specifications of Korea Advanced Pyroprocess Facility Plus.

Hot cell	Size (L × W × H, m)	Volume (m^3)	Atmosphere	Quantity	Thickness (mm)			Concrete
					Wall	Floor	Ceiling	
SF reception	54 × 12 × 12	7,776	Air	1	1,500	700	1,000	High density
Head-end	65 × 12 × 12	9,360	Air	1	1,500	700	1,000	High density
Pyroprocessing	75 × 22 × 12	19,800	Argon	1	1,500	700	1,000	High density
Waste treatment 1	18.1 × 8.6 × 8	1,245	Air	1	700	1,200	1,000	High density
Waste treatment 2	18.1 × 8.6 × 8	1,245	Air	1	700	1,200	1,000	High density
Waste treatment 3	27 × 12 × 8	2,592	Air	1	1,500	1,200	1,500	High density
Chemical	24 × 9 × 6	1,296	Air	2	500	1,000	500	Normal
UCl_3 production	24 × 9 × 6	1,296	Argon	1	500	1,000	700	Normal

equipment lifetime is relatively short as they cannot factor in the time value of the currency. Accordingly, when high-priced equipment is operated for a long time, like the pyroprocess facility, there is a need to develop a new depreciation method that can calculate the pyroprocess unit cost accurately.

This study analyzed the problems that may result when the existing depreciation method is applied to the pyroprocess facility, and then developed the advanced decelerated depreciation method (ADDM), a method that is most suitable for the pyroprocess facility.

There are some differences between this study and the existing cost estimation studies for pyroprocess facility. The differences will now be summarized: first, a new depreciation method called ADDM, which is appropriate for the pyroprocessing facility was developed; second, a reasonable way of costing capital investment using ADDM, instead of applying all capital investment to the pyroprocessing unit cost in the beginning was suggested; third, by calculating the depreciation cost similar to the cost trends of the direct material cost and the direct labor cost, confidence in the result of the cost estimation was enhanced; and fourth, the impact of depreciation cost on the pyroprocessing unit cost from the initial to final stage of a pyroprocessing facility's lifetime was analyzed in detail for each year.

2. Materials and methods

2.1. *Cost object: KAPF+*

Costs that are injected into the KAPF+, which is a commercial pyroprocess facility, can be divided into direct material cost, direct labor cost, and manufacturing indirect cost [6–8]. For example, direct materials that are injected into the pyroprocess include platinum and LiCl-KCl [3,4]. The pyroprocess process cost can be expressed as the sum of the three cost elements (direct material cost, direct labor cost, and manufacturing indirect cost), as shown in Eq. (1).

$$TPC = \sum_{t}\sum_{i} DMC_{i,t} + \sum_{t}\sum_{j} DLC_{j,t} + \sum_{t}\sum_{k} MOHC_{k,t} \qquad (1)$$

where TPC = the total product cost of the pyroprocess, t = time (period), $DMC_{i,t}$ = the direct material cost of the i^{th} process at time t, $DLC_{j,t}$ = the direct labor cost of the j^{th} process at time t, and $MOHC_{k,t}$ = the manufacturing overhead cost of the k^{th} process at time t.

The direct material cost and direct labor cost can trace the costs incurred using an economic method, and they increase in proportion to the output. However, indirect manufacturing cost cannot trace the costs incurred using an economic

Table 3 – Main process devices in pyroprocess facility.

No.	Equipment/device	Quantity	Remark
1	Electrolytic reducer & accessories	8	125 kgHM/d
2	Reducer cathode distillation & accessories	4	250 kgHM/d
3	Electro refiner & accessories	8	125 kgHM/d
4	Refiner salt distiller	4	250 kgHM/d
5	U ingot manufacturing equipment & accessories	4	470 kgHM/d
6	LCC Electrowinner	4	20 kgHM/d
7	Cd distillation & U/TRU melting furnace	4	
8	RAR draw down	4	11 kgHM/d
9	LiCl Crystallization/Furnace	4	125 kg LiCl-KCl/d
10	Storage tank & salt transfer system	10	
11	LiCl Solid salt separation	2	
12	LiCl Solidification apparatus	4	
13	LiCl/KCl Oxidative precipitation apparatus	4	
14	LiCl/KCl Solid salt detaching device	4	
15	LiCl/KCl Layer separation apparatus	2	
16	LiCl/KCl Vacuum distillation apparatus	4	
17	U ingot packaging system	2	
18	U/TRU/RE/Zr ingot packaging system	2	

HM, heavy metal; RAR, residual actinides recovery; RE, rare earth; U/TRU, uranium/transuranium.

Table 4 – The costs of Korea Advanced Pyroprocess Facility Plus.

Category	5% discounted amount (unit: k$)	Ratio (%)
Capital investment	261,180	33.5
Operation & maintenance cost	496,219	63.7
Decommission & disposal cost	21,988	2.8
Total	779,386	100

method. Accordingly, the pyroprocess process cost can be expressed as Eq. (2).

$$TPC = NUP_t\left(\sum_t\sum_i DMCu_{i,t} + \sum_t\sum_j DLCu_{j,t}\right) + \sum_t\sum_k MOHC_{k,t} \tag{2}$$

where NUP_t = number of units produced at time t, $DMCu_{i,t}$ = the direct material cost per unit of the i^{th} process at time t, and $DLCu_{j,t}$ = the direct labor cost per unit of the j^{th} process at time t.

Moreover, the direct material and labor costs are affected by the transaction price by each unit in the market, and the manufacturing indirect cost is determined by the production amount. Thus, the pyroprocess process unit cost can be expressed as Eq. (3).

$$UC_{pyro} = DMCu + DLCu + \frac{\sum_t MOHC_t}{P} \tag{3}$$

where UC_{pyro} = unit cost of the pyroprocess, $DMCu$ = the direct material cost per unit, $DLCu$ = the direct labor cost per unit, $MOHC_t$ = the manufacturing overhead cost at time t, and P = the quantity of production (unit: kgHM).

2.2. Existing depreciation methods

The depreciation cost entails allocating the costs of the asset that contributed to the creation of profit (output) during the durable period based on the structured method, and is a process for handling the cost incurred due to profit creation [13–17]. Thus, the principle of matching costs with revenue needs to be satisfied. Moreover, because the depreciation cost is a cost element of the indirect manufacturing cost, it exerts a significant effect on the pyroprocess' unit cost as well. Currently, the straight-line method and fixed percentage of the declining-balance method are depreciation methods that are often used for the tangible assets at a nuclear power plant facility [18]. These two types of methods are easy to calculate [13,19].

Table 5 – Durable period due to the load factor.

Load factor (%)	Durable period (y)	The total production during a year (kgHM)	The total production during durable period (kgHM)
100	15	400,000	6,000,000
70	25	280,000	7,000,000
55	40	220,000	8,800,000

HM, heavy metal.

Table 6 – Input data for the depreciation cost estimation of Korea Advanced Pyroprocess Facility Plus.

Classification	Criteria
Tangible assets cost	Processing building: $442,318,000 Pyroprocess system (equipment): $416,313,000
Residual value of tangible assets	Processing building: $442,318 (0.1% of total) Pyroprocess system (equipment): $416,313 (0.1% of total)
Depreciation method	Straight-line method Fixed percentage of declining-balance method Advanced decelerated depreciation method
Decelerated depreciation rate	3%, 5%

2.2.1. Straight-line method

The straight-line method entails deducting the residual value from the purchasing cost, and then depreciating the same amount during each period. The straight-line method is suitable when the economic benefit is manifested in a consistent manner during the depreciation period as the time lapses by, and is expressed as Eq. (4) [14–17].

$$DC_t^{SLM} = \frac{(PC_A - RV_A)}{N} \tag{4}$$

where DC_t^{SLM} = depreciation cost of the straight-line method at year t, PC_A = the purchasing cost of tangible assets A, RV_A = the residual value of tangible assets, and N = durable period (unit: year).

2.2.2. Declining-balance method

The declining-balance method is also referred to as the accelerated depreciation method. A considerable amount is depreciated during the initial stage of the depreciation, and the depreciated amount decreases as time passes. This method implies that the productivity is high during the initial

Table 7 – The depreciation cost in the straight-line method.

Durable years	Category	Depreciation cost ($)
15	Building	27,754,200
	System	29,487,867
	Annual depreciation cost	57,242,067
25	Building	16,652,520
	System	17,692,720
	Annual depreciation cost	34,345,240
40	Building	10,407,825
	System	11,057,950
	Annual depreciation cost	21,465,775

Table 8 – The depreciation cost in the fixed percentage of declining-balance method with the durable period of 15 years.

Year	Depreciation cost ($)		
	Building	System	Total
1	153,637,255	163,234,209	316,871,464
2	96,938,554	102,993,823	199,932,378
3	61,164,093	64,984,709	126,148,802
4	38,591,934	41,002,580	79,594,513
5	24,349,864	25,870,879	50,220,743
6	15,363,726	16,323,421	31,687,146
7	9,693,855	10,299,382	19,993,238
8	6,116,409	6,498,471	12,614,880
9	3,859,193	4,100,258	7,959,451
10	2,434,986	2,587,088	5,022,074
11	1,536,373	1,632,342	3,168,715
12	969,386	1,029,938	1,999,324
13	611,641	649,847	1,261,488
14	385,919	410,026	795,945
15	243,499	258,709	502,207

stage of machinery use, and that the productivity decreases during the latter end. Declining-balance methods include the fixed percentage of the declining-balance method, the double declining-balance method, and the sum-of-the years' digits method [14–17].

2.2.2.1. *Fixed percentage of declining-balance method.* The fixed percentage of the declining-balance method is for calculating the depreciation cost by multiplying a tangible asset's base book value amount by a specific rate for each period. Since the base book value amount is the residual amount after deducting the cumulative depreciation cost amount from the purchasing cost, the depreciation cost is recognized significantly in the beginning, and decreases as time passes. Moreover, a nonzero residual value needs to be assumed to avoid the depreciation rate of 1. This method can calculate the depreciation rate from Eq. (5), and the depreciation cost can be calculated using Eq. (6).

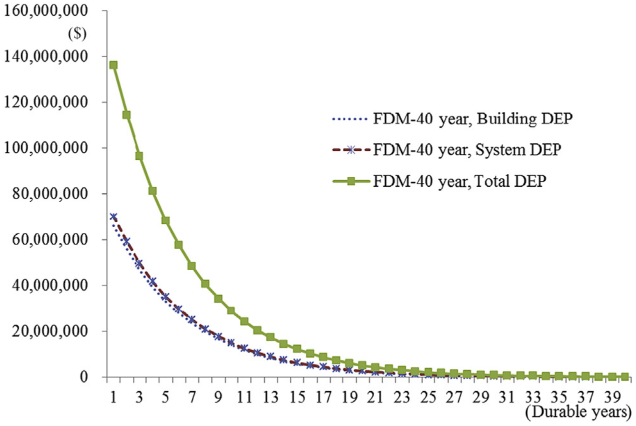

Fig. 2 – The depreciation cost in the fixed percentage of declining-balance method (FDM) with the durable period of 40 years.

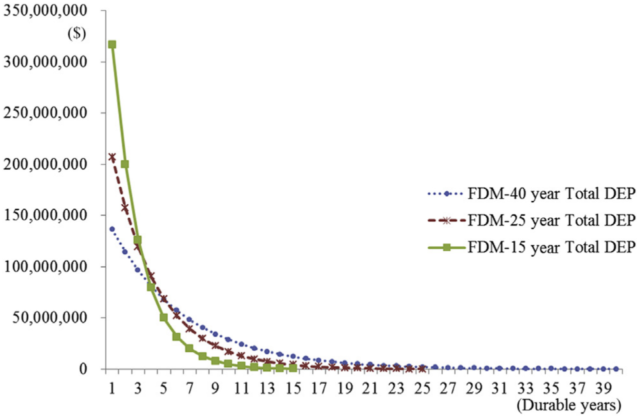

Fig. 3 – A comparison of total depreciation cost in the fixed percentage of declining-balance method (FDM).

$$DBRFP_A = 1 - \sqrt[N]{\frac{RV_A}{PC_A}} \tag{5}$$

where $DBRFP_A$ = declining balance rate of tangible assets A.

$$DC_t^{FPDBM} = BV_A \times DBRFP_A \tag{6}$$

where DC_t^{FPDBM} = the depreciation cost of the fixed percentage of declining-balance method at t years, and BV_A = the book value of tangible assets A at the beginning of year.

2.2.2.2. *Double declining-balance method.* As shown in Eq. (7), the double declining-balance method is calculated by assuming that the depreciation rate of the straight-line method is double. Its advantages are that the depreciation rate calculation is easy and that a considerable amount is depreciated in the beginning.

$$DC_t^{DDBM} = BV_A \times \frac{2}{N} \tag{7}$$

where DC_t^{DDBM} = the depreciation cost of the double declining-balance method at t years.

Table 9 – The depreciation cost in the advanced decelerated depreciation method with the durable period of 15 years (discount rate 3%).

Year	Depreciation cost ($)		
	Building	System	Total
1	22,383,726	23,781,926	46,165,653
2	23,055,238	24,495,384	47,550,622
3	23,746,895	25,230,246	48,977,141
4	24,459,302	25,987,153	50,446,455
5	25,193,081	26,766,768	51,959,849
6	25,948,874	27,569,771	53,518,644
7	26,727,340	28,396,864	55,124,204
8	27,529,160	29,248,770	56,777,930
9	28,355,035	30,126,233	58,481,268
10	29,205,686	31,030,020	60,235,706
11	30,081,857	31,960,920	62,042,777
12	30,984,312	32,919,748	63,904,060
13	31,913,842	33,907,340	65,821,182
14	32,871,257	34,924,561	67,795,817
15	33,857,395	35,972,297	69,829,692

Table 10 – The depreciation cost in the advanced decelerated depreciation method with the durable period of 15 years (discount rate 5%).

Year	Depreciation cost ($)		
	Building	System	Total
1	19,292,897	20,498,028	39,790,925
2	20,257,542	21,522,929	41,780,471
3	21,270,419	22,599,076	43,869,495
4	22,333,940	23,729,030	46,062,969
5	23,450,637	24,915,481	48,366,118
6	24,623,168	26,161,255	50,784,424
7	25,854,327	27,469,318	53,323,645
8	27,147,043	28,842,784	55,989,827
9	28,504,395	30,284,923	58,789,318
10	29,929,615	31,799,169	61,728,784
11	31,426,096	33,389,128	64,815,224
12	32,997,401	35,058,584	68,055,985
13	34,647,271	36,811,513	71,458,784
14	36,379,634	38,652,089	75,031,723
15	38,198,616	40,584,693	78,783,309

2.2.2.3. Sum-of-the years' digits method. As shown in Eq. (8), the sum-of-the years' digits method is a method with which the depreciation cost is calculated by multiplying the amount of residual value by the share of the inverse order of the remaining durable period for the sum of the durable period.

$$DC_t^{SYDM} = (PC_A - RV_A) \times \frac{RDP_A}{\sum_{n=1}^{N} n} \tag{8}$$

where DC_t^{SYDM} = depreciation cost of sum-of-the years' digits method at t years, RDP_A = the residual durable period of tangible assets A.

2.2.3. *Compound interest method*

The compound interest method is a decelerated depreciation method that is the most used in the financial engineering field. The compound interest method can be classified into an annuity method and sinking fund method. This method is characterized by factoring in the currency's time value. In other words, this is a method that recognizes the depreciation cost at a low level during the initial durable period while a significant depreciation cost is recognized as the time lapses. Moreover, this depreciation cost is the recuperated cost that was injected to purchase tangible assets during the durable period [20–23].

The annuity method assumes that the acquisition of tangible assets is an investment for profit acquisition, and thus perceives net cash flow for each period's income as a depreciation cost. In other words, it is assumed as the process of acquiring interest received from the principal recovery and specific investment profit rate injected into the tangible asset. Accordingly, the depreciation cost can be expressed as Eq. (9) [21,23].

$$DC_t^{AM} = \left[PC_A - \frac{RV_A}{(1+r)^N}\right] \times \frac{r \cdot (1+r)^N}{(1+r)^N - 1} \tag{9}$$

where DC_t^{AM} = depreciation cost of an annuity method at t years, and r = the interest rate.

A sinking fund method recognizes a specific amount as a depreciation cost. At the same time, capital that corresponds to that depreciation cost is operated, and the sum of the principle and interest is laid in the same way as the initial depreciation amount used to calculate the cost that can replace a tangible asset. The depreciation cost by each year is calculated using Eq. (11) after obtaining the amount of the sinking fund (*SINKF*) by using Eq. (10) first [20,22].

$$SINKF = (PC_A - RV_A) \times \frac{r}{(1+r)^N - 1} \tag{10}$$

$$DC_t^{SFM} = SINKF + (r \cdot ADC_{t-1}) \tag{11}$$

Table 11 – A comparison of total depreciation cost in the advanced decelerated depreciation method (discount rate 3%).

Year	Total depreciation cost ($)		
	15 y	25 y	40 y
1	46,165,653	23,550,420	11,387,489
2	47,550,622	24,256,933	11,729,113
3	48,977,141	24,984,641	12,080,987
4	50,446,455	25,734,180	12,443,416
5	51,959,849	26,506,206	12,816,719
6	53,518,644	27,301,392	13,201,221
7	55,124,204	28,120,433	13,597,257
8	56,777,930	28,964,046	14,005,175
9	58,481,268	29,832,968	14,425,330
10	60,235,706	30,727,957	14,858,090
11	62,042,777	31,649,796	15,303,833
12	63,904,060	32,599,290	15,762,948
13	65,821,182	33,577,268	16,235,836
14	67,795,817	34,584,586	16,722,911
15	69,829,692	35,622,124	17,224,599
16	–	36,690,788	17,741,336
17	–	37,791,511	18,273,577
18	–	38,925,256	18,821,784
19	–	40,093,014	19,386,437
20	–	41,295,805	19,968,031
21	–	42,534,679	20,567,071
22	–	43,810,719	21,184,084
23	–	45,125,041	21,819,606
24	–	46,478,792	22,474,194
25	–	47,873,156	23,148,420
26	–	–	23,842,873
27	–	–	24,558,159
28	–	–	25,294,904
29	–	–	26,053,751
30	–	–	26,835,363
31	–	–	27,640,424
32	–	–	28,469,637
33	–	–	29,323,726
34	–	–	30,203,438
35	–	–	31,109,541
36	–	–	32,042,827
37	–	–	33,004,112
38	–	–	33,994,235
38	–	–	35,014,062
40	–	–	36,064,484

where DC_t^{SFM} = the depreciation cost of the sinking fund method at t years, and ADC_{t-1} = the accumulated amount of depreciation cost at $t - 1$ years.

2.3. *New depreciation cost estimation method*

2.3.1. *Problems of the straight-line method and the fixed percentage of declining-balance method in case of the pyroprocess facility's depreciation*

Two problems result when the pyroprocess facility's depreciation cost is calculated by using the straight-line method and the fixed percentage of declining-balance method. First, when the pyroprocess facility's load factor is consistent, a consistent depreciation cost should be incurred during the durable period. However, in the case of the fixed percentage of the declining-balance method, an excessive depreciation cost is calculated during the initial stage of the depreciation. Secondly, the depreciation cost is included in the U/TRU ingot manufacturing cost as a part of the manufacturing indirect cost. Moreover, direct material cost and direct labor cost, which are the other elements that comprise the production cost, increase steadily with time. When perceived from this viewpoint, it is viable to claim that the indirect manufacturing cost also increases with time. However, a consistent depreciation cost results in a straight-line method with a time lapse, while the depreciation cost decreases significantly with time in the case of the fixed percentage of declining-balance method. Accordingly, the straight-line method and fixed percentage of declining-balance method cannot satisfy the cost flow of the indirect manufacturing cost.

In the end, the straight-line method and fixed percentage of the declining-balance method, which are often used today, are not appropriate for the pyroprocess facility. Meanwhile, the compound interest method is known to be appropriate for a real estate transaction or lease related industry [20–22]. Thus, a new depreciation method is needed to increase the pyroprocess unit cost's accuracy level.

2.3.2. *New method: ADDM*

ADDM is a method that complements the existing sinking fund method. In other words, although the sinking fund method factors in the currency's time value, it is used to obtain the sinking fund. To calculate the depreciation cost, the interest income of the accumulated depreciation cost is added to the sinking fund. Thus, the sinking fund method is inappropriate for calculating the depreciation cost of the pyroprocess facility's tangible asset itself. Accordingly, this paper presents a new depreciation method called ADDM. To utilize ADDM, the purchasing cost for the pyroprocess facility's tangible asset factors in the currency's time value to be expressed, as in Eq. (12).

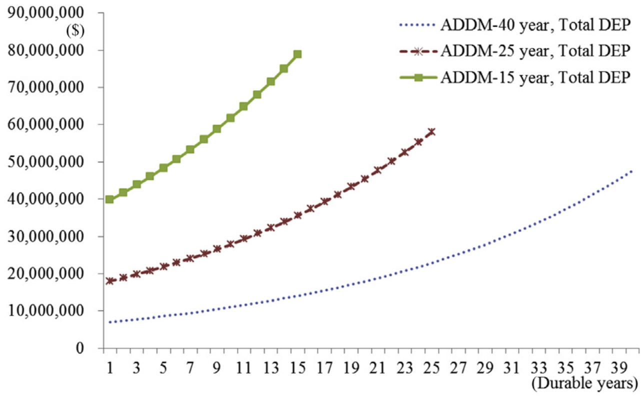

Fig. 4 – A comparison of total depreciation cost in the advanced decelerated depreciation method (ADDM; discount rate 5%).

$$DC_{t_0}^{ADDM} = \frac{\left(PC_A^B + PC_A^E\right)}{\sum_{n=1}^{N}\left(1+d_r\right)^{n-1}} \tag{12}$$

where $DC_{t_0}^{ADDM}$ = the 1st-year depreciation cost of ADDM, PC_A^B = the purchasing cost of building A, PC_A^E = the purchasing cost of equipment A, N = durable period (unit: year), and d_r = the deceleration rate (discount rate).

Finally, the depreciation cost of ADDM can be expressed as Eq. (13).

$$DC_t^{ADDM} = \left(PC_A^B + PC_A^E\right) \times \frac{\left(1+d_r\right)^{t-t_0}}{\sum_{n=1}^{N}\left(1+d_r\right)^{n-1}} \tag{13}$$

where DC_t^{ADDM} = the depreciation cost of ADDM at t years and t_0 = the beginning year of depreciation (year of purchase).

2.4. *Input data*

For the data input to calculate depreciation cost, the cost data on the KAPF+'s building and equipment, identified by the pyroprocess facility's conceptual design, are used [3]. For example, the equipment's durable period was classified depending on the pyroprocess facility's load factor. In other words, KAPF+ calculated a 55% load factor, but the durable period will be reduced due to reasons such as the decreased endurance of the machinery and so forth when the load factor

Table 12 – A comparison of total depreciation costs with the durable period of 15 years.

Year	Total depreciation cost ($)			
	SLM	FDM	ADDM (3%)	ADDM (5%)
1	57,242,067	316,871,464	46,165,653	39,790,925
2	57,242,067	199,932,378	47,550,622	41,780,471
3	57,242,067	126,148,802	48,977,141	43,869,495
4	57,242,067	79,594,513	50,446,455	46,062,969
5	57,242,067	50,220,743	51,959,849	48,366,118
6	57,242,067	31,687,146	53,518,644	50,784,424
7	57,242,067	19,993,238	55,124,204	53,323,645
8	57,242,067	12,614,880	56,777,930	55,989,827
9	57,242,067	7,959,451	58,481,268	58,789,318
10	57,242,067	5,022,074	60,235,706	61,728,784
11	57,242,067	3,168,715	62,042,777	64,815,224
12	57,242,067	1,999,324	63,904,060	68,055,985
13	57,242,067	1,261,488	65,821,182	71,458,784
14	57,242,067	795,945	67,795,817	75,031,723
15	57,242,067	502,207	69,829,692	78,783,309

ADDM, advanced decelerated depreciation method; FDM, fixed percentage of declining-balance method; SLM, straight-line method.

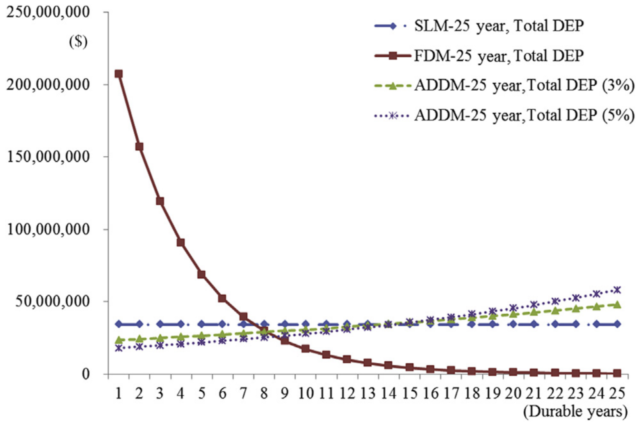

Fig. 5 – A comparison of total depreciation costs with the durable period of 25 years.

increases. Accordingly, this study estimated the facility's maximum durable period as 40 years, and assumed the depreciation periods as 40 years, 25 years, and 15 years according to the load factor. The depreciation period and production amount following the load factor are shown in Table 5.

The residual value of the equipment for the pyroprocess facility was assumed to be 0 because it is necessary to dispose of the equipment when the durable period expires in the case of a commercial pyroprocess facility [24]. In the case of a fixed percentage of a declining-balance method, however, calculation is made possible when a residual value exists. Thus, 0.1% of the purchasing cost was assumed as the residual value.

To carry out a comparative analysis of the depreciation cost following ADDM and the existing depreciation method, the straight-line method and fixed percentage of declining-balance method were used. These are the depreciation methods that are used the most today. Moreover, discount rates of 3% and 5% were assumed. Table 6 shows the input data needed for calculating KAPF+'s depreciation cost.

3. Results and discussion

3.1. *Depreciation cost estimation results*

3.1.1. *Straight-line method*

The depreciation cost following the straight-line method is shown in Table 7. The depreciation cost is incurred consistently during the durable period of equipment. The depreciation cost by year for the durable period of 40 years was calculated as 38% when it comes to the depreciation cost by year with a durable period of 15 years.

3.1.2. *Fixed percentage of declining-balance method*

The depreciation cost calculation results following a fixed percentage of declining-balance method are shown in Table 8 (durable period of 15 years) and Fig. 2 (durable period of 40 years). The depreciation rates were calculated as 0.369 and 0.159 in the case of durable periods of 15 years and 40 years, respectively. The depreciation cost of the 1st year out of the durable period of 15 years was approximately 2.37 times the depreciation cost with a durable period of 40 years.

A graph that compares the total depreciation cost by each durable period is shown in Fig. 3. After the depreciation cost for the 1st year is calculated, the depreciation cost decreases significantly as time passes. The depreciation rate is the highest in the case of the depreciation cost of the 1st year when the durable period is 15 years. Thus, a significant depreciation cost is incurred during the initial stage, and this decreases with time.

3.1.3. *ADDM*

As shown in Eq. (14), ADDM's validity was verified by confirming that the sum of the depreciation cost by year, and the sum of the purchasing cost of the building and equipment, are the same for the durable period. For example, in the case of a facility life period of 40 years with a deceleration rate of 3%, the sum of the depreciation cost by year, and the sum of the purchasing cost of the building and equipment were $858,631,000 each. Thus, they were the same.

$$\sum_t DC_t^{ADDM} = PC_A^B + PC_A^E \tag{14}$$

The depreciation cost of ADDM, calculated by applying a discount rate of 3%, is as shown in Table 9; and calculated by applying a discount rate of 5%, as shown in Table 10 (durable period of 15 years).

Graphs comparing ADDM's total depreciation costs are shown in Table 11 (showing a discount rate of 3%) and Fig. 4 (showing a discount rate of 5%). Also in Fig. 4, the depreciation cost is as low in the beginning when the discount rate increases in the case of ADDM. However, the depreciation cost increases toward the latter end.

3.2. *Comparative analysis of the depreciation cost of the three methods*

The depreciation costs of the three methods (straight-line method, fixed percentage of declining-balance method, and ADDM) are shown in Table 12 (durable period of 15 years), Fig. 5 (durable period of 25 years), and Fig. 6 (durable period of 40 years).

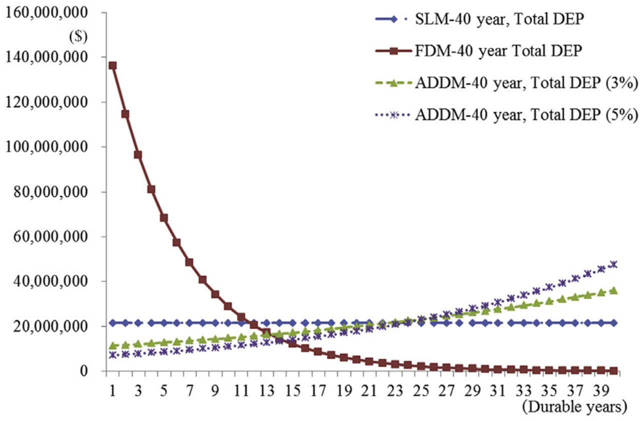

Fig. 6 – A comparison of total depreciation costs with the durable period of 40 years. ADDM, advanced decelerated depreciation method; FDM, fixed percentage of declining-balance method; SLM, straight-line method.

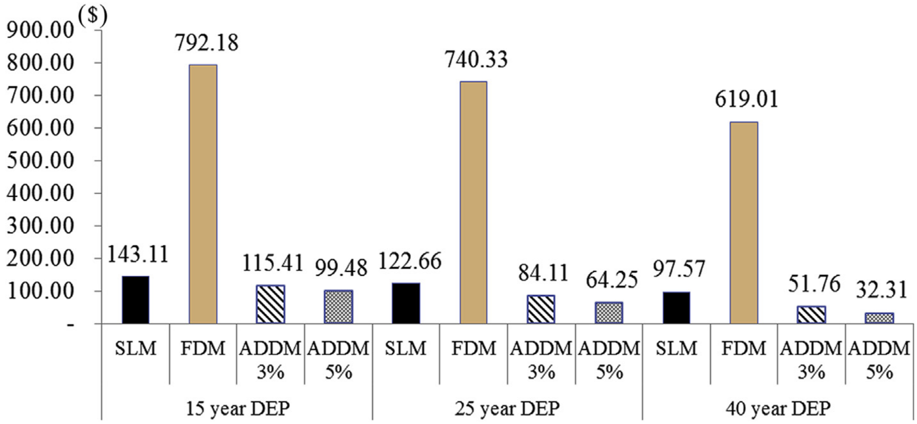

Fig. 7 – The 1st-year depreciation cost (unit: $/kg heavy metal).

As shown in Table 12, the depreciation cost was calculated for the 1st year on the basis of the straight-line method. The depreciation cost of the fixed percentage of the declining-balance method was 553.56%, compared to that of the straight-line method. In addition, the depreciation cost of ADDM that assumed a discount rate of 3% was 80.56%, whereas the depreciation cost of ADDM, which assumed a discount rate of 5% was 69.51%.

In the case of the final year of depreciation, when the straight-line method was used as the standard, the depreciation cost of the fixed percentage of the declining-balance method was 0.88%. In addition, the depreciation cost of ADDM that assumed a discount rate of 3% was calculated as 121.99%, whereas ADDM, which assumed that the discount rate was 5%, was calculated as 137.63%. Accordingly, the fixed percentage of the declining-balance method entails calculating the depreciation cost excessively in the beginning compared to the straight-line method. Meanwhile, the pyroprocess facility's depreciation cost was incurred appropriately during the pyroprocess facility's durable period in the case of ADDM.

Fig. 7 shows the depreciation cost per unit for the 1st year that factored in the load factor. In the case of the straight-line method, the depreciation cost per unit was $143.11/kgHM when the durable period is 15 years, $122.66/kgHM in the case of 25 years, and $97.57/kgHM in the case of 40 years. As for the fixed percentage of declining-balance method, it was $792.18/kgHM in the case of 15 years, $740.33/kgHM in the case of 25 years, and $619.01/kgHM in the case of 40 years. Likewise, the depreciation cost was excessive. Compared to the straight-line method, ADDM led to a relatively lower depreciation cost. For example, when the durable period was assumed to be 15 years and the discount rate was 3%, the depreciation cost was calculated to be $115.41/kgHM.

Fig. 8 shows the calculation of the depreciation cost that factored in the load factor. The depreciation cost of the final year was calculated to be completely opposite to that of the 1st year. In the case of ADDM, the depreciation cost is higher than that of the straight-line method. In the case of the depreciation cost that was calculated with the straight-line method, the amount for the final year was the same as that of the 1st year. However, in the case of the ADDM that factored in a 3% discount rate, the depreciation costs were calculated as $174.57/kgHM, $170.98/kgHM, and $163.93/kgHM in the case of durable periods of 15 years, 25 years, and 40 years, respectively.

Moreover, as for the depreciation cost of the ADDM that assumed a durable period and deceleration rate of 40 years and 5%, respectively, it was disclosed that 4.14% and 27.74% are taken up among the pyroprocess unit costs ($781/kgHM, reference year = 2009) [10–12]) in the beginning and at the end, respectively. Accordingly, it was found that the

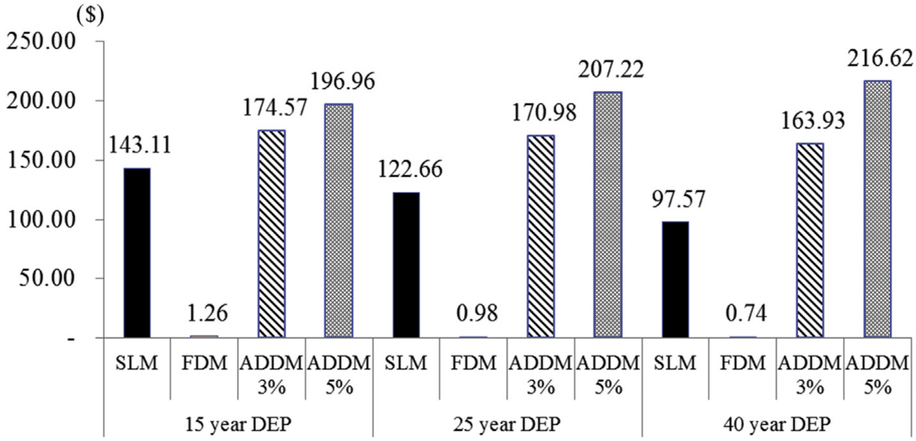

Fig. 8 – The ending-year depreciation cost (unit: $/kg heavy metal).

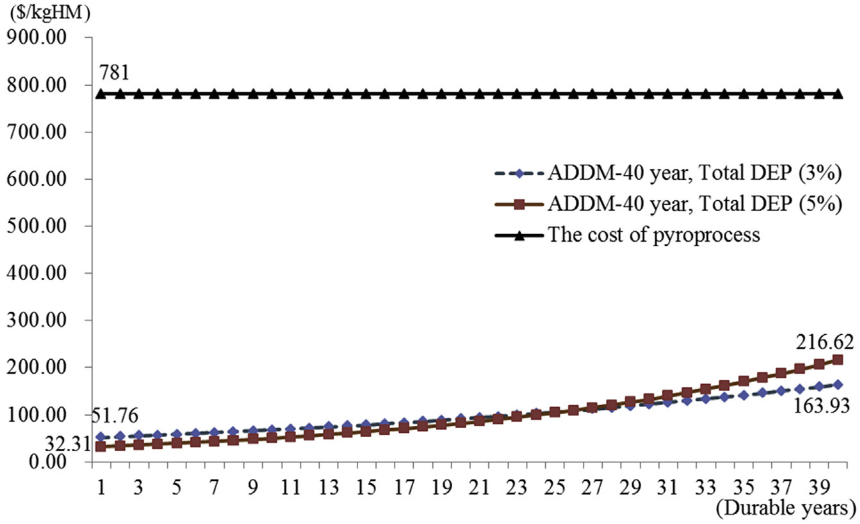

Fig. 9 – A comparison between the pyroprocess cost and depreciation cost of advanced decelerated depreciation method (ADDM).

depreciation cost can exert a significant effect on the pyroprocess unit cost. Thus, the pyroprocess unit cost may be distorted when the rational depreciation method is not applied.

Since the depreciation cost is a component of the indirect manufacturing cost, it is necessary to maintain a trend that is similar to the cost flow of the direct material cost and direct labor cost. In other words, if the direct material cost and direct labor cost continue to increase, it is viable to increase the indirect manufacturing cost as well.

Fig. 9 presents the comparison between the pyroprocess cost and depreciation cost of ADDM. In addition, Fig. 10 shows the trends of the direct material cost, direct labor cost, and indirect manufacturing cost. The cost of platinum (a direct material cost that is an anode electrode material for the electrochemical reduction process) [25] and direct labor cost [26] continued to increase from 2000 to 2014. Platinum increased two-fold in 15 years while the labor cost increased by approximately 2.3 times. From this cost flow aspect, the depreciation cost of ADDM that applied a 5% discount rate, manifested a trend similar to that of the direct labor cost and direct material cost. Accordingly, it is possible to claim that ADDM is a depreciation method suitable for a pyroprocess facility.

3.3. *Conclusion*

When the engineering cost estimation method is used to calculate the pyroprocess unit cost, it is not possible to calculate the capital investment every year as it is assumed that the capital investment is invested during the initial stage of the pyroprocess facility's construction. Accordingly, the pyroprocess unit cost uncertainty increases. However, when a depreciation method is used, it is possible to allocate capital investment appropriately during the facility's life period. Thus, in the case of a facility with a long life, such as a pyroprocess facility, it is possible to calculate the increasingly

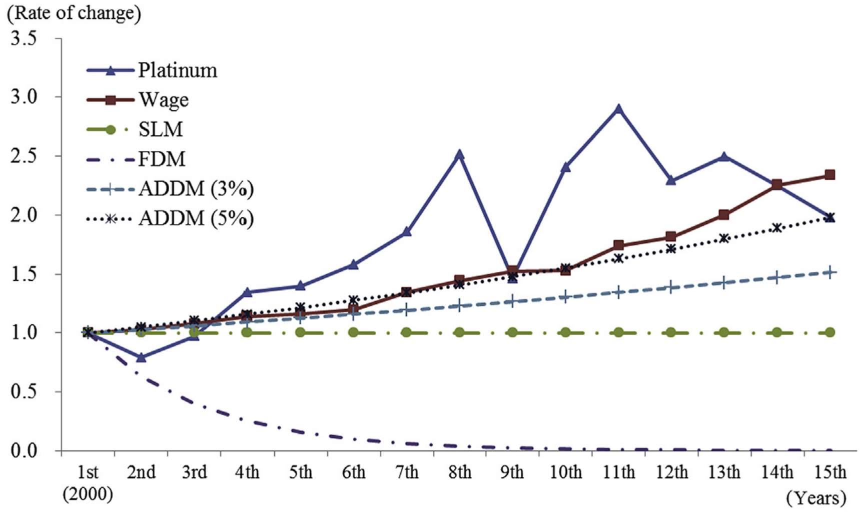

Fig. 10 – The trend of raw material (platinum) cost, labor cost (wage) and depreciation costs. ADDM, advanced decelerated depreciation method; FDM, fixed percentage of declining-balance method; SLM, straight-line method.

accurate pyroprocess unit cost. However, since the straight-line method and fixed percentage of declining-balance method are used mostly as depreciation methods today, it is necessary to decide on a depreciation method after analyzing which method is suitable for a pyroprocess facility.

KAPF+, which is a commercialization facility, was set as the cost object, and the existing methods (straight-line method and fixed percentage of declining-balance method) used today and the depreciation cost of the ADDM were subjected to a comparative analysis. The results are as follows. First, in case of the straight-line method that calculated the durable period as 40 years, and in case of ADDM that factored in a 5% deceleration rate, the difference in the depreciation costs of $65.26/kgHM and $119.05/kgHM resulted during the 1st year and final year, respectively. Accordingly, it was found that there is a significant difference in terms of the cost of the capital investment every year depending on the depreciation method. Second, since the depreciation cost is a component of the manufacturing indirect cost, it is necessary to maintain a trend that is similar to that of the direct labor cost in addition to the direct material cost. In this respect, the depreciation cost of ADDM can be considered the most suitable depreciation method for a pyroprocess facility. In the end, the depreciation cost of ADDM that assumed a durable period of 40 years and a deceleration rate of 5% was found to take up 4.14% and 27.74% during the 1st year and final year among the pyroprocess unit costs ($781/kgHM, reference year = 2009) [10–12].

However, this study may be limited in the sense that the building and equipment costs of the KAPF+ that this paper used as the input data are not actually incurred costs. Instead, they are the costs that were estimated based on the conceptual design. This problem will be resolved when a commercial pyroprocess facility is constructed in the future.

Conflicts of interest

The authors declare no conflict of interest.

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