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Cost analysis of a commercial pyroprocess facility on the basis of a conceptual design in Korea

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ABSTRACT

This study postulated a commercial pyroprocess facility (KAPF+: Korea Advanced Pyroprocess Facility Plus) with a processing capacity of 400 tons/year as a cost object, and utilized an engineering cost estimation method based on a conceptual design to present the results of the total cost and unit cost estimation. According to the calculation results, the total cost and unit cost were calculated with k$779,386 and $781/kgHM, respectively. Moreover, the key cost driver was manifested as the operating and maintenance costs. In particular, equipment replacement cost was identified as an important cost driver. In addition, for an increasingly accurate cost estimation, the calculation results and allocation method of the indirect cost were reanalyzed. Finally the pyroprocess unit cost increased $5 when calculated the indirect cost using the labor time as the allocation standard. Meanwhile, the pyroprocess unit cost increased $22 as a result of allocating the indirect cost using the uniform labor cost as the cost allocation standard. Accordingly, an indirect cost allocation standard was manifested as the factor that exerts a significant effect on the pyroprocess unit cost.

1. Introduction

After the Fukushima Nuclear Plant disaster in Japan, interest in nuclear power safety and economic viability has been increasing (Chino et al., 2011). In addition, as the Yucca Mountain repository construction project of the US was canceled, there is a need to carry out extensive researches to find an economic alternative for the back-end fuel cycle (Bunn et al., 2003; MIT, 2010). Against this background, the pyro-SFR (Sodium-cooled Fast Reactor) fuel cycle alternative perceived as an advanced fuel cycle alternative is gaining attention as a latent future nuclear power technology that is safe and economically viable (Kim et al., 2013). Accordingly, an evaluation of the pyroprocess facility cost for spent fuel is an essential prerequisite for identifying the viability of pursuing the after pyro-SFR fuel cycle business (Kim et al., 2013). This study calculated the pyroprocess unit cost based on the KAPF+'s conceptual design against this background (KAERI, 2011). An engineering cost estimation method based on the conceptual design was utilized as a manufacturing cost calculation method because, to this day, a commercialized pyroprocess facility does not exist (Kang, 2010). Accordingly, pyroprocess facility unit cost was estimated by using the material volume based on facility's conceptual design (Albers, 1995). Moreover, a levelized unit cost estimation method was utilized to calculate the pyroprocess unit cost. This method presents the facility capacity as a precondition since it entails calculating the pyroprocess unit cost by dividing the total cost of the pyroprocess facility converted into the present value into the production volume converted into the present value (Challal and Tkiouat, 2012). Therefore, the total costs and unit costs for the pyroprocess facility depend on the facility size.

Since the economic environment of each of the advanced nuclear power nations that are developing pyroprocess technology is different, they are trying to draw out a pyroprocess unit cost that suits their own national environment (Lee et al., 2005). International organizations such as OECD/NEA are considering the process for justifying or normalizing the cost data in order to alleviate the difference in total and unit costs resulting from a difference in each nation's material and labor costs (OECD/NEA, 2013).

The pyroprocess facility cost can be classified mainly into capital cost, operating and maintenance cost, and decommissioning and disposal cost, while the capital cost can be segmented into the direct cost, indirect cost, and contingency (Humphreys, 1984). The direct cost can be tracked down easily using an economic method, while indirect cost cannot be tracked down with such a method (Mowen et al., 2012). Moreover, the contingency was calculated as a certain percentage of the sum of the direct

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and indirect costs to complement the uncertainty of total cost (Kwon, 2013).

When the capital cost is calculated among the pyroprocess costs, the cost estimator can arbitrarily calculate the indirect cost in proportion to the direct cost or allocate the indirect cost arbitrarily during the facility lifetime using the allocation standard such as the work time or labor cost (Shin, 2005). Accordingly, an indirect cost allocated arbitrarily is bound to be uncertain since it is not a real cost (Park, 2005). In other words, a difference in the indirect cost's present value may result due to the diverse indirect cost allocation methods and juncture for injecting capital and cost flow (Kang, 2010). Accordingly, the indirect cost's uncertainty can significantly affect the pyroprocess unit cost. This can be used as information data for the uncertainty of the pyroprocess unit cost for the decision-maker. In the end, information on the production cost's accuracy level can provide not only the quality level of production cost calculation result (Han, 2012), but can also increase the reliability of the estimated pyroprocess unit cost.

In general, a manufacturing cost analysis, which includes uncertainty uses a method of expressing a probabilistic method or unit cost as a specific scope instead of a deterministic method in order to increase the reliability (Kim, 2007). However, a probabilistic method requires a considerable amount of data in order to produce a distribution with high reliability since the pyroprocess unit cost is calculated using the probability distribution such as a triangular distribution or uniform distribution for the input variable, but there are not many cost related data since the pyroprocess facility is not yet commercialized.

Therefore, this study calculated the pyroprocess unit cost using the following process. First, pyroprocess facility's direct cost was calculated based on the conceptual design. Second, the total amount of indirect cost was calculated based on expert judgment using calculated direct cost as the allocation standard. Third, calculated indirect cost was allocated yearly using various arbitrary allocation standards during the pyroprocess facility's lifetime. Fourth, the capital cost, operating and maintenance cost, and decommissioning and disposal cost were added to calculate total pyroprocess cost. Fifth, the pyroprocess unit cost was calculated using this value. Finally, this study analyzed the effect of the cost flow of diverse indirect costs on the pyroprocess unit cost.

2. The conceptual design of KAPF+

2.1. Chemical background

KAPF+ is an independent facility equipped with supportive facility and waste storage facility, which receives an annual of 400 tHM/year of PWR SF(Spent Fuel)s, performs processes of the disassembling and cutting, decladding, and voloxidation, collects excess uranium ingots by the electro-refining after the electrochemical reduction, and recovers the residual uranium and TRU as an ingot form by the electro-winning. For instance, the electrochemical reactions regarding the electrochemical reduction and electro-refining are as follows.

Electrochemical reduction:
Cathode:

$$UO_2 + 4e^- \rightarrow U + 2O^{2-}$$

$$TRUO_2 + 4e^- \rightarrow TRU + 2O^{2-}$$

$$Li^+ + e^- \rightarrow Li$$

$$U_xO_y + 2yLi \rightarrow xU + yLi_2O$$

$$TRU_xO_y + 2yLi \rightarrow xTRU + yLi_2O$$

$$2Li_2O \rightarrow 2Li^+ + O^{2-}$$

Anode:

$$O^{2-} \rightarrow 1/2O_2 + 2e^-$$

Electro-refining:
Cathode:

$$U^{3+} + 3e^- \rightarrow U$$

Anode:

$$U \rightarrow U^{3+} + 3e^-$$

$$Nd \rightarrow Nd^{3+} + 3e^-$$

$$Pu \rightarrow Pu^{3+} + 3e^-$$

Chemical reaction:

$$RE_2O_3 + 2UCl_3 \rightarrow 2RECl_3 + UO + UO_2$$

$$UCl_3 + Pu \rightarrow PuCl_3 + U$$

Electro-winning:
Cathode:

$$U^{3+} + 3e^- \rightarrow U$$

$$TRU^{3+} + 3e^- \rightarrow TRU$$

$$RE^{3+} + 3e^- \rightarrow RE$$

Anode:

$$RE \rightarrow RE^{3+} + 3e^-$$

$$2Cl^- \rightarrow Cl_2 + 2e^-$$

As shown in Fig. 1, spent fuel constituents are partitioned according to Gibbs free energy of formation of chloride at 500 °C. Most uranium can be recovered by a solid cathode and TRUs can be co-deposited at liquid cadmium cathode together with part of uranium. Nobel metal retains with cladding materials in the anode basket to be treated as metal waste. Alkaline earth metal, alkaline metal and residual rare earth are accumulated in the molten salt which will be treated and fabricated as final ceramic waste.

However, the individual TRU such as Pu is not able to be separated purely because of the extremely narrow difference in Gibbs free energy during electro-winning process.

The main characteristic of reference SF for the pyroprocesses facility is specified as shown in Fig. 2. ORIGEN ver. 2.1 code is used to calculate the composition of SFs.

As shown in Fig. 3, KAPF+ is enclosed by internal and external double fences centered on the main building, which includes the head-end cell, pyroprocess cell, and the supportive facilities, following the 10CFR73 physical protection requirements. An area for KAPF+ is estimated to be about 272,000 m^2, i.e., 680 m in length and 400 m in width. Fig. 4 shows the overview of pyroprocess, and the design requirements of KAPF+ are shown in Table 1 (KAERI, 2011).

SF of 4.5 wt% initial enrichment, 55,000 MWd/tU burnup, and 10 years of cooling were adopted as a reference material introduced into the KAPF+. A burnup simulation of the SF using the ORIGEN code revealed that the reference SF contains 1.489 wt% TRU, which implies that about 5.624 tTRU would be recovered after processing 400 tHM SFs. The recovered U-TRU ingots are used in SFR nuclear fuel fabrication.

The major processes in KAPF+ are composed of SF reception, SF storage, head-end processes performed in a head-end cell, and pyroprocesses operated in the pyroprocesses cell. SF assembly disassembling, rod chopping, decladding/voloxidation, high