Transactions of the Korean Nuclear Society Autumn Meeting
Goyang, Korea, October 24-25, 2019

Comparison of Nuclear Fuel Cycle Economics under Current Energy Policies in Korea

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1. Introduction

Nuclear power is a huge energy source that accounts for about 30% of Korea's electric power generation. However, the government has not yet decided the nuclear fuel cycle policy involving spent fuel disposal in spite of the long 40 years of nuclear power generation. Despite the fact that the filling rate of spent fuel in the onsite storage facilities is more than 90%, the repository site has not yet been determined. Although the current government's nuclear power phase out policy does not promote the construction of additional nuclear power plants beyond Shin-Kori Units 5 and 6, the nuclear fuel cycle policy should be considered separately from the energy transition policy because of not only the existing spent fuels, but also those to be generated in the future.

There are some fuel cycle options that can be considered in Korea. The first one is the Once-Through(OT) scheme, which is to geologically dispose the spent fuel discharged directly from nuclear power plants. This is the permanent disposal scheme not involving any reprocessing. The second one which was once considered is the DUPIC (Direct Use of PWR spent fuel in CANDU) scheme, which is to reprocess the spent fuel of PWRs for reuse in CANDU reactors. The third one is the PWR-MOX scheme, which is to reprocess the PWR spent fuel employing PUREX (Plutonium Uranium Redox Extraction) process for reuse as the mixed oxide (MOX) fuel in PWRs. The last one is the pyro-processing/SFR (sodium-fast reactor) scheme, which is to reprocess U and TRU in the PWR spent fuel for used in fast reactors (SFR).[1] The DUPIC and PWR-MOX are, however, not considered feasible in the current international politics environment in which the nonproliferation issue is the most important consideration in the nuclear fuel cycle options. In this regards, we compare the economics of the direct disposal (OT) and the pyro-processing schemes. Note the pyro-processing/SFR scheme can be the representative fuel cycle of Korea.

For the comparison, LFCCs (Levelized Fuel Cycle Costs) calculated based on the material flow and the amount of spent fuel of each fuel cycle are to be used as an indicator. The IAEA Nuclear Fuel Cycle Simulation System (NFCSS) [2] is adopted to obtain the mass flow. In the material flow calculation using NFCSS, a computational model is constructed based on the actual nuclear power plant operation data of Korea of the past and also of the future to assure the realism.

2. Methods

Unlike the previous studies [1,3] where the LFCC was calculated in the equilibrium model for specific amount of power generation (1TWh), this study applies the inflation and discount rates using the dynamic model by reflecting the actual operating status (No. of NPPs, the capacity factors of each NPP, the amount of power generation, etc.) of the nuclear power plants. By forecasting more precise material flows and the amount of spent fuel, we tried to compare the costs of the two fuel cycle policies. The first phase of the analysis is to estimate the material flow and spent fuel generation. The second phase is to calculate the LFCC for each fuel cycle based on the predicted spent fuel generation.

In the first phase, we used NFCSS to calculate the mass flow and the amount of spent fuels. NFCSS can provide annual material mass flows and the spent fuel masses for the entire nuclear fuel cycle (involving mining, refining, enrichment, processing, power generation, intermediate storage, reprocessing, and disposal) based on the input data such as the characteristics of fuel (concentration, composition, reprocessing, etc.), power plant type (PWR, PHWR, SFR, etc.), and specifications (output, operating period, capacity factor, efficiency, etc.), and the reprocessing schemes, etc. An example material flow diagram of a direct disposal fuel cycle implemented through NFCSS is shown in Fig. 1.

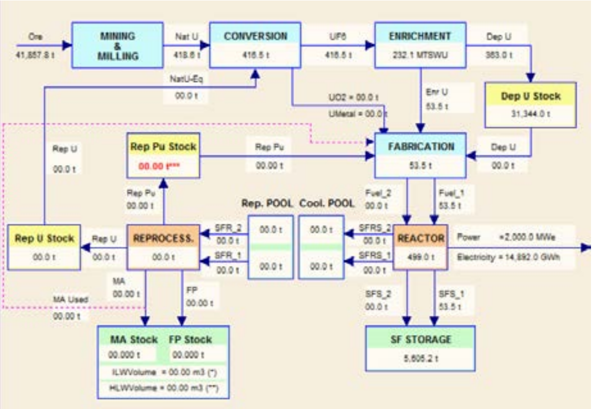

Fig. 1. NFCSS – mass flow chart of a direct disposal fuel cycle option

In this way, the amount of the material generated at each stage can be calculated, and the unit costs for each stage can be applied to calculate the total cost for the fuel cycle. The fuel cycle cost is calculated based on the following input data: total power generation, uranium mining/enrichment/refining costs, spent fuel interim storage (aqueous, dry) costs, spent fuel geological disposal costs, spent fuel reprocessing costs, spent fuel transportation costs, and facilities construction and operating cost. The equations used are given in Table 1.

Table 1: Equations involved in fuel cycle cost calculation

Calculation Equation		
Uranium	$C_u(t) = \frac{Q_u(t) \cdot UC_u \cdot (1+E_u)^{t-YR_b}}{(1+D_t)^{t-YR_b}}$	(1)
Conversion	$C_c(t) = \frac{Q_c(t) \cdot UC_c \cdot (1+E_c)^{t-YR_b}}{(1+D_t)^{t-YR_b}}$	(2)
Enrichment	$C_e(t) = \frac{Q_e(t) \cdot UC_e \cdot (1+E_e)^{t-YR_b}}{(1+D_t)^{t-YR_b}}$	(3)
Fabrication	$C_f(t) = \frac{Q_f(t) \cdot UC_f \cdot (1+E_f)^{t-YR_b}}{(1+D_t)^{t-YR_b}}$	(4)
Storage	$C_s(t) = \frac{Q_s(t) \cdot UC_s \cdot (1+E_s)^{t-YR_b}}{(1+D_t)^{t-YR_b}}$	(5)
Disposal	$C_d(t) = \frac{Q_d(t) \cdot UC_d \cdot (1+E_d)^{t-YR_b}}{(1+D_t)^{t-YR_b}}$	(6)
Reprocessing	$C_r(t) = \frac{Q_r(t) \cdot UC_r \cdot (1+E_r)^{t-YR_b}}{(1+D_t)^{t-YR_b}}$	(7)
Cost of direct disposal	$TC_d = C_u(t)+C_c(t)+C_e(t)+C_f(t)+C_s(t)+C_d(t)$	(8)
Cost of reprocessing	$TC_d = C_u(t)+C_c(t)+C_e(t)+C_f(t)+C_s(t)+C_r(t)+C_d(t)$	(9)
where, Cx(t) : cost of fuel cycle component, Qx(t) : Quantity of materials, UCx(t) : Unit cost, Ex : Escalation rate, t : Target year, YRb : Base year, Dt : Discount rate Subscript x, u : natural uranium, c : conversion, e : enrichment, f : fabrication, s : storage, d : disposal, r : reprocessing		

2.1. NFCSS Reliability Verification

Since the NFCSS is a program focused on generating material mass flows for a fuel cycle option, it is necessary to verify the reliability of the NFCSS before predicting the future material flows and spent fuel amount. To verify the reliability of NFCSS, we used the actual plant's operational data: the amounts of power generation and spent fuel data obtained for the period from 2004 through 2018. During this period, the average capacity factor of the nuclear power plants was 85.98% and about 880 tons of spent fuel has been produced annually.

In order to calculate the amount of generation, material flow and spent fuel generation in the same period, it is necessary to input the parameters of the power plan, and the capacity factor. The parameters of each power plant type are given in Table 2. The specific capacity factors of a plant which are different from those of other plants are provided individually.

Table 2: Reactor data for NFCSS calculation

	PWR	CANDU	SFR
Capacity(MWe)	600~1400	700	600
Nominal capacity factor(%)	85	85	85
Efficiency(%)	33	30	39.4
Fuel enrichment(%)	3.50	0.71	22.1
Discharge burnup(GWD/tHM)	35.15	7.00	93.00
No. of batches	3	-	6
Conversion ratio	-	-	0.6067

To verify the reliability of NFCSS calculation results, total electricity generation and spent fuel amount of all nuclear power plants were summed and compared. In the case of spent fuel generation, the calculated value from NFCSS shows less fluctuation compared to the actual value due to the characteristics of the NFCSS calculation method. Note that because the use of 18-month cycle which cannot be properly incorporated in the NFCSS annual spent fuel calculation, such annual fluctuations appear. The relative error of spent fuel generation shown in figure 2 is 3%, indicating that the estimation by NFCSS is reliable.

Fig. 2. NFCSS calculation results and actual data

2.2. Future Models and Fuel Cycle Scenarios Setting

The most important thing in specifying the future prediction model is to reflect the future operation plan of the nuclear power plants in Korea. For this, the current government's energy transition roadmap and the 8-th basic plan for electricity supply and demand are employed. It is assumed that no additional construction and life extension of nuclear power plants would be made beyond Shin Kori Units 5 and 6. It also assumed the capacity factor will be reduced to about 70%. However, in a long-term model, it would be reasonable to reflect general data rather than the effect of a specific policy. Therefore, the capacity factor of all the nuclear plants beyond 2020 is set to 85%. The number and the total capacity of the operating plants after 2020 are given in Fig. 3.

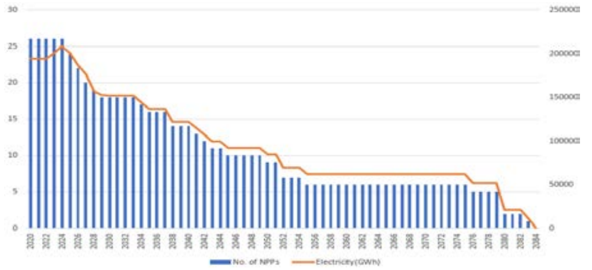

Fig. 3. Currently projected number and total capacity of nuclear power plants

The fuel cycle scenarios are modeled based on the future plan of nuclear power plant construction, and the direction of the fuel cycle policy was assumed to be determined by 2030, considering the situation of saturation of the spent fuel onsite storage facilities. Three scenarios were set up for effective comparison.

Scenario 1 is the scheme of continuously storing all accumulated spent fuel (case 1. No action). Scenario 2 is the direct geological disposal (case 2. Once-through). Scenario 3 is reprocessing of used fuel (case 3. Pyro-processing).

2.3. Calculation of LFCC

It is important to accurately calculate the material flow in the fuel cycle to get the exact equalization fuel cycle cost, but it is also important to determine the reasonable unit cost. In particular, the forecasting of future costs must take into account the uncertainty of price fluctuations. In this study, the LFCC was calculated by applying the unit price composed of triangular distribution to reflect the uncertainty of price fluctuation.

In addition, the important costs of the pyro-processing are R&D and construction costs and annual SFR operation cost. Especially the main difference between Case 2 and Case 3 in this study is the operation of the SFR, so the construction and operating costs of the pyro-processing facility must be considered. Additional cost for the construction and operation of the SFR is used the values from the previous study [6] and investment costs(R&D and construction costs) are applied evenly over the operation period of the SFR. The cost considering the capacity of the SFR is given in Table 3.

Table 3: Investment and operation costs of SFR facilities

Description	Estimated cost (kUSD)
Direct cost (site preparation, processing building support facilities)	77,095
Indirect cost (design, licenses, startup and testing, initial training)	272,918
Contingency	183,873
Operation & Management cost (staff, materials, equipment replacement, utilities)	24,795
Total	558,681

Another important factor to consider in forecasting future costs is the inflation and discount rates. Generally, the inflation rate and the discount rate are predicted and reflected in order to calculate the expected LFCC. Eqns. (1) through (9) reflect the inflation rate and the discount rate already. However, because the purpose of this study is to compare each fuel cycle policy's economics, we can apply a different method instead of reflecting uncertain inflation rate. The study calculates the costs incurred from 2030 to 2090 on a yearly basis, based on material flows, the amount of spent fuel generated, and the unit costs. And it compares directly the estimated costs with other fuel cycle costs at the same year. In this way, eliminating inflation and discount rates for the future is possible by assuming the same value for the two.

This approach increases the uncertainty in future accurate cost projections, but makes it easier to assess the relative costs between the fuel cycles and reduce errors due to inaccurate inflation. The following graph shows the relative ratio of the LFCC and the total costs of each case. The reference case is Case 1.

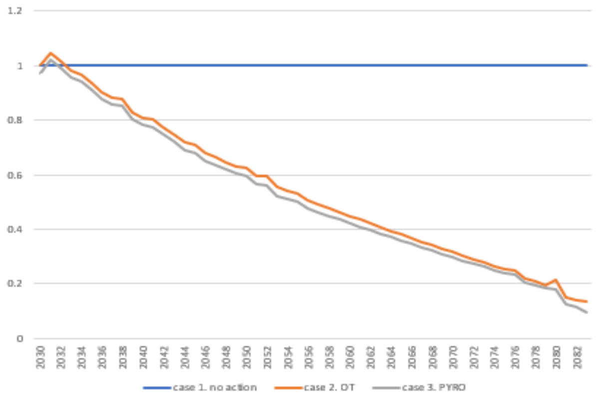

Fig. 4. LFCC comparison by nuclear fuel cycle

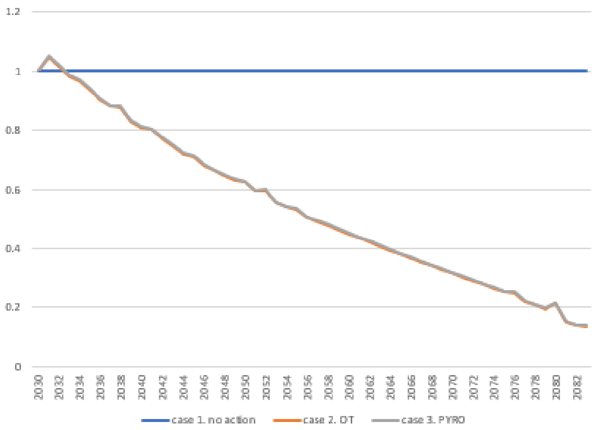

Fig. 5. Total cost comparison by nuclear fuel cycle

3. Conclusion

Based on the prediction of the nuclear power plant operation beyond 2030, we compared the costs of the currently feasible fuel cycle policies. Looking at the graph of Figure 4, both direct disposal and pyro-processing incur more costs than initially taking no action, but as the amount of spent fuel accumulates over time decreases, the LFCC and total cost are reduced. This means that a decision on nuclear fuel cycle policy should be made as soon as possible. In particular, it is noteworthy that the LFCC of pyro-processing is lower than direct disposal’s LFCC. This is in contrast to the results from previous studies. In the past studies, the LFCC of direct disposal was lower due to the expensive unit costs of the pyro-processing. However, in this study, the LFCC of the pyro-processing was lower than OT because of the increased power generation due to SFR operation. In the previous study, the LFCC is calculated based on the equilibrium model that produces 1TWh of electricity generation. Therefore, when additional power is produced in SFR, the amount of PWR power is reduced. But this is not realistic. This is because if we operate the SFRs to produce additional power, there is no reason to lower the operation rate of the PWR in real world. This study suggests that LFCC of pyro-processing may be the cheapest in more realistic model. And again, as the electricity generation increased, LFCC also decreased and became more economical.

REFERENCES

[1] Byung Heung Park and Won il Ko, External Cost Assessment for Nuclear Fuel Cycle, Journal of Nuclear Fuel Cycle and Waste Technology Journal Abbreviation, Vol.13 No.4, p.243-251, 2015.
[2] IAEA, Nuclear Fuel Cycle Simulation System(NFCSS) User Manual, IAEA, 2011.
[3] Won il Ko, and Fanxing Gao, Economic Analysis of Different Nuclear Fuel Cycle Options, Science and Technology of Nuclear Installations, 2012.
[4] Won il Ko, Fanxing Gao, and Sung Ki Kim, Economic Analysis of Several Nuclear Fuel Cycles, the Korean Nuclear Society Spring Meeting, 2012.
[5] Sungki Kim, Wonil Ko Saerom Youn, Ruxing Gao, Sunsig Bang, Advanced fuel cycle cost estimation model and its cost estimation results for three nuclear fuel cycles using a dynamic model in Korea, Nuclear Engineering and Design, vol.293, p.159-165, 2015.
[6] S.K.Kim, W.I.Ko, and Yoon Hee Lee, Economic Viability of Metallic Sodium-Cooled Fast Reactor Fuel in Korea, Science and Technology of Nuclear Installations, vol.2013, 2013.