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Burnup effect on nuclear fuel cycle cost using an equilibrium model

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1. Introduction

In order to improve economics of nuclear fuel cycle costs accounting for about 20% of the total cost of electricity, extended burnup and thermal efficiency, which has been an economic challenge in many countries producing nuclear energy, can be an essential method to meet this objective [1]. The degree of fuel burnup is an important technical parameter to the nuclear fuel cycle, being sensitive and progressive to reduce the total volume of process flow materials and eventually cut the nuclear fuel cycle costs [2]. This paper performed the sensitivity analysis of the total nuclear fuel cycle costs to changes in the technical parameter by varying the degree of burnups in each of the three nuclear fuel cycles using an equilibrium model. Important as burnup does, burnup effect was used among the cost drivers of fuel cycle, as the technical parameter. The fuel cycle options analyzed in this paper are three different fuel cycle options as follows: PWR-Once Through Cycle(PWR-OT), PWR-MOX Recycle, Pyro-SFR Recycle. These fuel cycles are most likely to be adopted in the foreseeable future.

2. Nuclear Fuel Cycle Cost

2.1 Methodology

To calculate NFCC(Nuclear Fuel Cycle Cost), an equilibrium model was mainly used. The Equilibrium model is used at batch study, assuming that the whole system is in a steady state and that the mass flow as well as electricity production throughout the fuel cycle is in an ideal equilibrium state. This model calculated material flow of the certain generation quantity to calculate fuel cycle costs with the reference value about unit cost of each process [3]. The Equilibrium model do not apply the time dependent cost price functions of realistic cases, which is used by dynamic model so that it can conduct fuel cycle simulation for the future in long-terms with unavoidable huge uncertainty. In this paper, for computational convenience and reducing uncertainty, the equilibrium model was used to calculate the material flow on a batch basis.

2.2 Material flow analysis

Fuel cycle cost is obtained on the basis of the material flow on a batch basis, the values of which is calculated by using an equilibrium model. The material flow is a method for the quantitative comparison regarding uranium utilization and waste generation between the three different nuclear fuel cycles. This paper sets up a total 1 TWh electricity generation in a "steady state" and calculates the material flow generated in each process of nuclear fuel cycle [3].

2.3 Cost estimation results

The nuclear fuel cycle cost is derived in a form of mills/kWh (1 mill=10^{-3} \$) by dividing the entire fuel cycle cost occurred at time t of the total electricity output over the time as follows:

$$NFCC = \frac{\sum_{stages} C_t^1 + \sum_{stages} C_t^2}{E_t} \qquad (1)$$

Where C_t^1 = the front end of the fuel cycle at time t, C_t^2 = the back end of the fuel cycle at time t, E_t = electric power generated at time t [4]. In this paper, fuel cycle cost covers the front-end of the fuel cycles to the final disposal and reprocessing. Equation (1) is a formula calculating NFCC using an equilibrium model.

Table 1. Share of nuclear fuel cycle unit cost

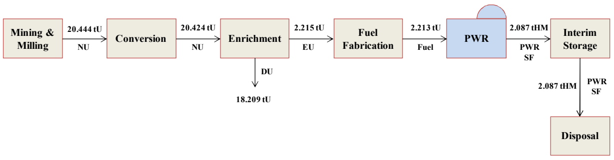
Category	PWR-OT		PWR-MOX		Pyro-SFR	
	Cost	Share	Cost	Share	Cost	Share
Uranium	3.07	45.89	2.28	33.77	1.85	27.90
Conversion	0.13	1.94	0.09	1.33	0.08	1.21
Enrichment	2.51	37.52	1.86	27.55	1.51	22.77
PWR Fuel Fabrication	0.57	8.52	0.42	6.22	0.34	5.13
MOX Fuel Fabrication	-	-	0.36	5.33	-	-
SFR Fuel Fabrication	-	-	-	-	1.14	17.19
Subtotal for Front-End	6.25	93.42	5.01	74.22	4.92	74.21
Transport & Dry storage	0.38	5.68	0.28	4.14	0.23	3.44
Reprocessing	-	-	1.39	20.59	-	-
Pyroprocessing	-	-	-	-	1.41	21.27
Reactor Loading	-	-	0.04	0.59	-	-
MOX Storage	-	-	0.02	0.29	-	-
disposal SF UO_2Packaging Cost	0.07	1.05	-	-	-	-
HLW Storage	-	-	0.02	0.29	-	-
HLW Disposal	-	-	0.01	0.14	-	-
Decay Storage(Cs/Sr)	-	-	-	-	0.07	1.05
Subtotal for Back-End	0.44	6.58	1.74	21.77	1.71	25.79
Total	6.69	100	6.75	100	6.63	100

Table 1 shows the calculation results of the three nuclear fuel cycles using an equilibrium model, except for nuclear reactor cost.

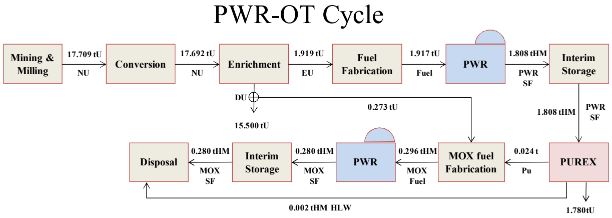
3. Sensitivity Analysis on burnup as a technical parameter of fuel cycle cost

Table 2. The input data to estimate nuclear fuel cycle costs

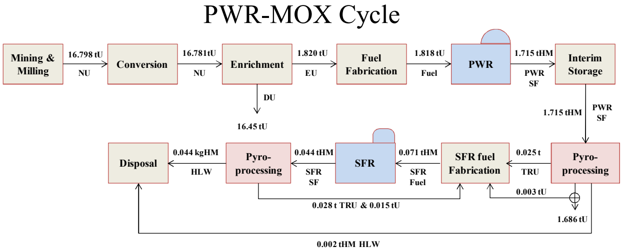
	PWR-OT	PWR-MOX	Pyro-SFR
Burnup (MTU/tHM)	55,000	65,000	55,000
Efficiency(%)	34.23	34.23	32.23
Annual loading(tU)	16.479	13.944	16.479
Capacity factor(%)	85	85	85
Annual elect. generation (GWh)	7,446	7,446	7,446
Consumption rate of HM	5.64	PWR 5.64 MOX 5.06	5.64
Annual discharge(tHM)	15.55	13.16	15.55



PWR-OT Cycle



PWR-MOX Cycle



Pyro-SFR Cycle

Figure. 1. Quantitative material flow analysis for 3 options

The current limit of burnup in Korea and the USA is 60,000 MWD/tHM and 62,000 MWD/tHM, respectively [5]. Accordingly, this paper performed sensitivity analysis of fuel burnup effect on nuclear fuel cycle cost from 45,000 MWD/ tHM of burnup to 62,000 MWD/ tHM of burnup.

Consequently, as shown in figure 2, typically for PWR-MOX cycle, when the burnup is 45,000 MWD/ tHM and 62,000 MWD/ tHM, the nuclear fuel cycle cost was about 9.75 Mills/kWh and 7.07 Mills/kWh, respectively. The sensitivity analysis on the burnup indicates that the PWR-MOX option depends more on the degree of burnup than any other fuel cycles, as shown in figure 2. Pyro-SFR cycle, however, turned out to be much less sensitive to burnup indicated by a smaller slope in Figure 2. In other words, the influence of the degree of burnup as a technical parameter on the nuclear fuel cycle costs can be significant.

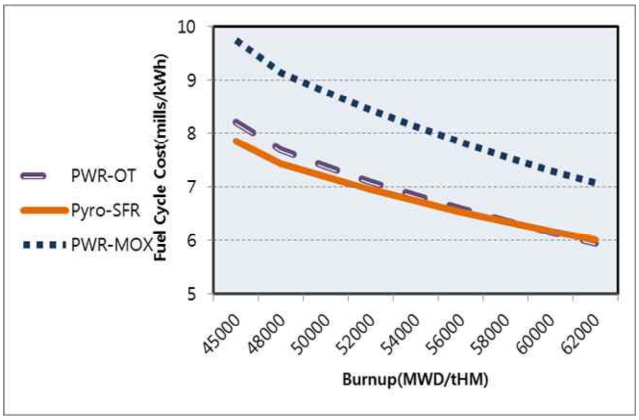


Figure 2. Sensitivity on burnup effect of three different nuclear fuel cycle cost

4. Conclusions

As a result of the sensitivity analysis on burnup effect of each three different nuclear fuel cycle costs, PWR-MOX turned out to be the most influenced by burnup changes. Next to PWR-MOX cycle, in the order of Pyro-SFR and PWR-OT cycle turned out to be influenced by the degree of burnup.

In conclusion, the degree of burnup in the three nuclear fuel cycles can act as the controlling driver of nuclear fuel cycle costs due to a reduction in the volume of spent fuel leading better availability and capacity factors. However, the equilibrium model used in this paper has a limit that time-dependent material flow and cost calculation is impossible. Hence, comparative analysis of the results calculated by dynamic model hereafter and the calculation results using an equilibrium model should be proceed.

Moving forward to the foreseeable future with increasing burnups, further studies regarding alternative material of high corrosion resistance fuel cladding for the overall nuclear power generation system is necessary.

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