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ECONOMIC VIABILITY TO BeO-UO_2 FUEL BURNUP EXTENSION

S. K. KIM[1,*], W. I. KO[1], H. D. KIM[1], YANGHON CHUNG[2], SUNGSIG BANG[2], and SHRIPAD T. REVANKAR[3]
[1]Korea Atomic Energy Research Institute
1045 Daedeokdaero, Yuseung-gu, Daejon 305-353, Republic of Korea
[2]Department of Management Science, Korea Advanced Institute of Science and Technology
373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea
[3]School of Nuclear Engineering, Purdue University
400 Central Drive West Lafayette, IN 47907, USA
[*]Corresponding author. E-mail : sgkim1@kaeri.re.kr

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This paper presents the quantitative analysis results of research on the burnup effect on the nuclear fuel cycle cost of BeO-UO_2 fuel. As a result of this analysis, if the burnup is 60 MWD/kg, which is the limit under South Korean regulations, the nuclear fuel cycle cost is 4.47 mills/kWh at 4.8wt% of Be content for the BeO-UO_2 fuel. It is, however, reduced to 3.70 mills/kWh at 5.4wt% of Be content if the burnup is 75MWD/kg. Therefore, it seems very advantageous, in terms of the economic aspect, to develop BeO-UO_2 fuel, which does not have any technical problem with its safety and is a high burnup & long life cycle nuclear fuel.

KEYWORDS : Burnup Effect, Nuclear Fuel Cycle, Cost Estimation, Beryllium, Credit Cost

1. INTRODUCTION

For continuous nuclear power generation, it is necessary to secure a new type of nuclear fuel that can increase not only technical safety but also economic profit. This means that this new nuclear fuel, which will be developed from now on, should be technically safe and produce an economic profit for commercialization as well. From this background, for past three years, Purdue University, located in the USA, has been researching and developing a BeO-UO_2 fuel that consists of mixed uranium and beryllium to meet the needs of technical safety and improvement of the volume of power generation.

In order to improve the performance of a new nuclear fuel, it is, in terms of the development of a new nuclear fuel, necessary to precede the development method with fundamentals that can increase the burnup by changing the ingredients of the nuclear fuel. This process is of much value in the development of a nuclear fuel which, by adding specific materials to it, has a higher performance than existing fuels, because the performance improvement of this new nuclear fuel made by changing the ingredients of the nuclear raw materials may finally lead to a revenue increase in terms of power generation, a profit increase for the electric power service providers, and a great contribution to the nuclear power generation industry.

However, it is very important to determine the optimum content rate of the mixed raw materials, because the mixed material is closely related to the direct material costs when increasing the burnup by mixing high cost materials. Thus, it is, above all, necessary to derive an optimum burnup in order to reduce the nuclear fuel cycle cost.

This study provides the analysis results for the burnup effect on nuclear fuel cycle costs when the cost object is BeO-UO_2 fuel. From the cost aspect, the burden increase of the raw material cost is first considered since the price of beryllium is relatively greater than that of uranium. From an efficiency aspect, the effect on the nuclear fuel cycle cost from increasing burnup, due to the improvement of the nuclear fuel's thermal conductivity, which may occur depending on the mixture ratio of beryllium, is calculated. The following Fig. 1 shows the conceptual effect of beryllium.

The raw material and manufacturing costs of the front-end fuel cycle cost are very important in terms of the economic analysis of the nuclear fuel cycle cost. Especially, a nuclear fuel that improves the burnup increases the volume of power generation, so it does have an additional relative effect on the reduction of radioactive waste. Considering the current difficulty of selecting a building site for a high-level waste repository, which problem various countries are suffering from, the BeO-UO_2 fuel, which provides great performance improvement, is the very nuclear fuel needed to reduce the disposal costs. Thus, nuclear fuel, like $BeO-UO_2$ fuel, for which the profit is greater than the increased input cost when adding specific materials to the existing uranium nuclear fuel, can stand in the spotlight as an original technology that improves the performance of nuclear fuel. Therefore, this paper provides the calculation results for the burnup effect on the nuclear cycle cost of $BeO-UO_2$ fuel. Also, this study reflects the calculation of credit cost related to the recycling of beryllium.

2. $BeO-UO_2$ FUEL

2.1 Characteristic of $BeO-UO_2$

The element beryllium is generally found in concentrations of less than 5% in ore. Beryllium oxide has a very high melting point, 2,570 ºC, and a great resistance to thermal shock. A characteristic of beryllium is its having resistance to atmospheric corrosion at a higher temperature compared to that of titanium or zirconium. Due to its lightness and solidity, in terms of its material characteristics, beryllium is widely used in materials development in the area of electricity and communications. However, the EPA provides that the upper limit for the environmental standard of beryllium is $0.01 \mu g/m^3$, because of its toxicity. In fact, beryllium can be fatal when a human inhales beryllium dust.

The increase of raw material costs raises the front-end fuel cycle cost and decreases the economic merit of $BeO-UO_2$ fuel. Also, this cost increase limits the increase of the volume of power generation due to the regulation of burnup. In addition, it is necessary to analyze how much the gap, due to the corrosion of covered tubes and the increase of pressure between pellets and tubes, affects safety when the burnup of nuclear fuel increases due to the inclusion of the beryllium ingredient.

According to the thermal analysis of $BeO-UO_2$ fuel carried out by Purdue University, beryllium has a good effect on the safety of $BeO-UO_2$ fuel (S. T. Revankar, W. Zhou and A. A. Solomon, 2009). Thus, there is no problem with the technical safety of $BeO-UO_2$ fuel (Kevin McCoy, Claude Mays, 2008), and it is concluded that the analysis of the burnup effect on $BeO-UO_2$ fuel from an economic aspect is valuable.

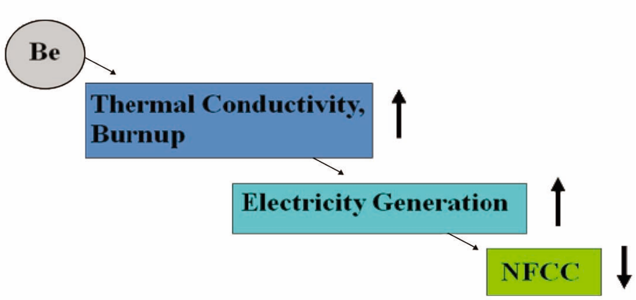

Fig. 1. The Conceptual Effect of Beryllium on the Nuclear Fuel Cycle Cost

2.2 Manufacturing Process of $BeO-UO_2$ Fuel

Comparing the production process of $BeO-UO_2$ fuel, which can be used for PWR, with that of uranium nuclear fuel, the process of $BeO-UO_2$ fuel is quite different in terms of the powder process, mixture process, mixture inspection process, and sintering process of a pellet. Especially, the process of cold pressing, which is a process prior to sintering, is, unlike that in the existing nuclear fuel process, an essential process for the homogeneous mixing of beryllium and uranium. The process of cold pressing that precedes the sintering process increases the soundness of the sintering [1]. Thus, the whole process of production is more complicated compared to the existing nuclear fuel process, since several processes are added. Especially, the work of a skilled worker is necessary during the process of inspecting the degree of a mixture's homogeneity in terms of beryllium and uranium. This process increases the cost of quality assurance, and this related cost change can be more accurately calculated by using the ABS (Activity Based Costing) method [2]. Generally, the accuracy of a cost change due to the increase of process complexity in relation to the manufacture of nuclear fuel depends on the degree of detailed necessary activities [3], and it is very important to reflect the complexity of the work in the cost for a more accurate cost calculation [2]. However, the manufacturing cost can be affected by the increase of labor costs due to the increment of work hours rather than to the increase of machinery costs when performing additional tasks using the same production line [4].

The manufacturing process of $BeO-UO_2$ fuel, done by using the Slug-Bisque and Green Granule method, is shown in the following Fig. 2 [1].

Fig. 3 shows $BeO-UO_2$ pellets. As shown in Fig. 3, (a), (b) and (c) give optical micrographs of the UO_2 powder after granulation, UO_2 powder after the self-milling and $BeO-UO_2$ pellets after sintering at 1700ºC for 5 h, respectively.

2.3 Price of Beryllium

There is currently a big difference between the price of beryllium, which is used as the raw material of $BeO-UO_2$ fuel, and the price of uranium. Thus, the production of nuclear fuel by mixing the relatively expensive raw materials leads to an increase of the direct material cost of nuclear fuel and, finally, to an increase of the front-end nuclear fuel cycle cost. The raw material cost of $BeO-UO_2$ fuel makes up about 34% of the nuclear fuel cycle cost in the case of considering the beryllium credit.

The power generation cost is divided into the fixed cost and the variable cost. The variable cost is the nuclear fuel cycle cost (NFCC). The related numerical expression is shown in equation (1) below. As shown in equation (1), the increase of the raw material costs raises the nuclear fuel cycle cost, which is a variable cost, and this finally becomes a factor that increases the power generation costs.

$$C = F_c + V_c = \frac{C_{uc} \cdot R}{T \cdot U_r \cdot (1 - I_c)} + NFCC \qquad (1)$$

where, F_c = fixed unit cost, V_c = variable unit cost, C_{uc} = construction unit cost($/kW), R = fixed charge rate, T = 8760(=365day x 24 hours), U_r = load factor, I_c = consumption rate in power plant, $NFCC$ = Nuclear Fuel Cycle Cost

However, the nuclear fuel cycle cost including the raw material cost can't be calculated easily since it contains the uncertainty of disposal cost [5]. For example, the disposal cost includes the social cost due to the difficulty of site selection of a radioactive waste repository, the uncertainty of the cost according to the disposal method and the uncertainty of the intermediate storage cost of the spent nuclear fuel according to the delay of the disposal time [6]. Although the disposal cost includes many uncertainties, world nations have performed research to calculate the exact cost in order to collect appropriate disposal funds from the power generation service providers every year since the disposal cost will demand a huge budget in the future [7]. The small accumulation of disposal funds does not allow for a smooth performance of a disposal business.

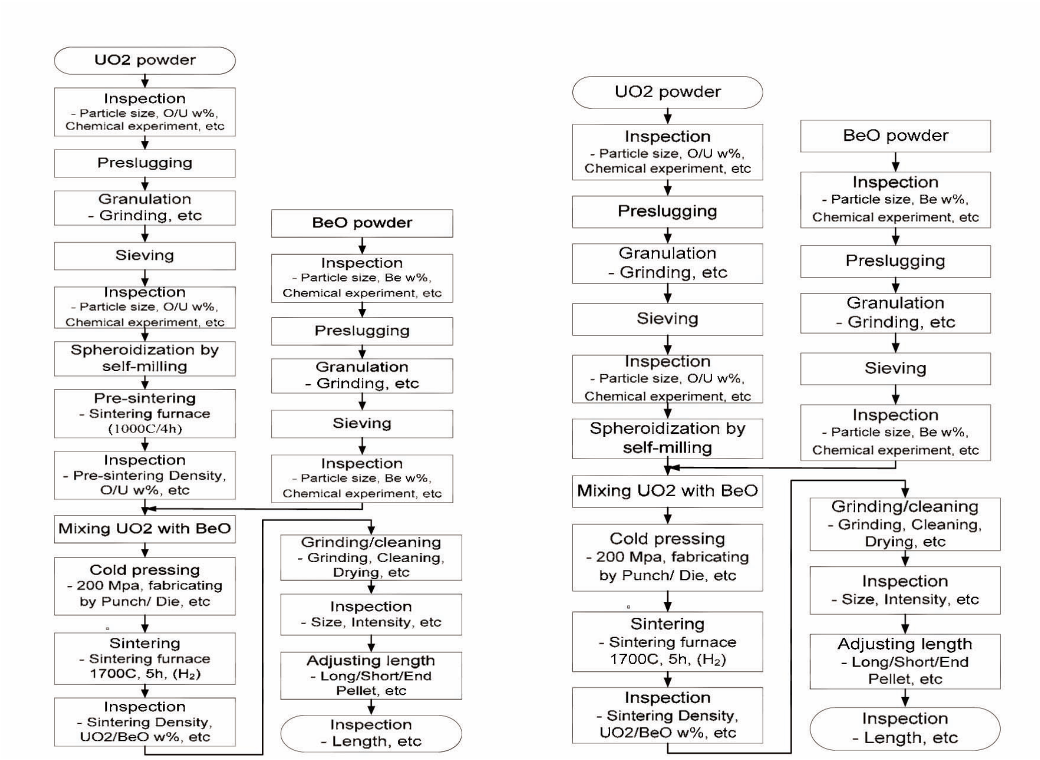

Fig. 2. Flowchart Describing the Fabrication Process for BeO-UO_2 Matrix Fuel Using SB and Green Granule Method

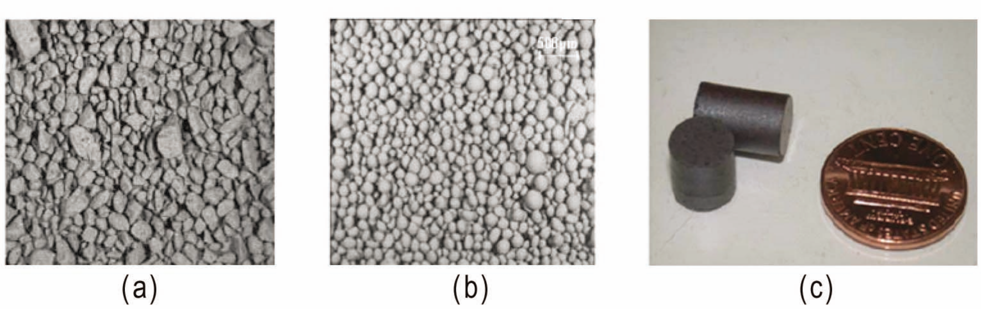

Fig. 3. (a) Optical Micrograph of the UO_2 Powder After Granulation, (b) After the Self-Milling and BeO Coating Step, and (c) BeO-UO_2 Pellets

On the other side, the excessive accumulation of disposal funds will bring about the loss of opportunity cost to a certain extent. Another factor of uncertainty are price changes of uranium and beryllium, which are used as raw materials. Any extreme price change, due to the instability of demand and supply of beryllium, can be a factor in decreasing the accuracy of the relative economic efficiency judgment of the BeO-UO_2 fuel compared with the uranium nuclear fuel. Therefore, it is necessary to calculate the exact nuclear fuel cycle cost when the price increase of beryllium is greater than that increase for uranium.

Currently, the price of beryllium is five times greater than that of uranium, so this can be an important factor in any decision concerning the economic efficiency of BeO-UO_2 fuel [8].

The price of beryllium stayed in a high price zone until 1990, and it was \$200 ~ \$400 per kg in the 2000s due to excessive supply by beryllium manufacturers. Recently, the price is on an increasing trend due to the increased demand in the area of electricity and communications [9]. The huge difference between the 1990s and the 2000s has become a factor for the increase of the uncertainty of beryllium prices.

From now on, the demand for beryllium is expected to increase in the area of cutting-edge industries, and it is forecasted that the price of raw materials will increase continuously. Thus, the burden of beryllium raw material costs can increase as time passes compared with the relatively low price of uranium. So, this increase of raw material cost will increase the manufacturing cost of beryllium-mixed nuclear fuel, and this high cost can be a huge obstacle to the mass production of BeO-UO_2 fuel.

2.4 Thermal Analysis of BeO-UO_2 Fuel

The temperature difference profile across a nuclear fuel pellet was calculated for the enhanced thermal conductivity oxide nuclear fuels. The results of these calculations are shown in Fig. 4, where the centerline temperature of the SB(Slug-Bisque)-BeO-UO_2 nuclear fuel was predicted to decrease by 217K from that of 95% dense UO_2, and the centerline temperature of the GG(Green Granule)-BeO-UO_2 nuclear fuel was predicted to decrease by 333K from that of 95% dense UO_2.

The SB-BeO-UO_2 fuel had the smaller decrease in centerline temperature, followed by the GG-BeO-UO_2 fuels. The GG-BeO-UO_2 fuel had the larger decrease in centerline temperatures [10]. Therefore, the BeO-UO_2 fuel satisfied the technical safety requirement, as shown in Fig. 4.

3. ANALYSIS OF NUCLEAR FUEL CYCLE COST

3.1 Calculation Method of Nuclear Fuel Cycle Cost

As shown in Fig. 5, nuclear fuel cycle costs can be broadly divided into the front-end nuclear fuel cycle cost and back-end nuclear fuel cycle cost on the basis of the point in time of the nuclear fuel loading and recharging.

The nuclear fuel cycle cost can be obtained by using not only the accounting method, but also the engineering method [11]. This means that nuclear fuel cycle costs can be calculated by totaling the values obtained by multiplying the quantity produced and each unit cost [12]. This calculation method is described in the "The economics of the nuclear fuel cycle", a report of the OECD/NEA issued in 1993 [13], and this method is used for most nuclear fuel cycle cost calculations due to the convenience of calculation after the publication of the report. Also, in terms of unit costs, the unit price, like the disposal unit cost, is an estimated cost, which is not an actual cost and may occur in the future, so it can be an important factor for deciding on the accuracy of the calculation results [14].

Examining the conversion process of the nuclear fuel cycle cost into the present value, the necessary cost is first calculated by estimating the cost demands; the appropriate discount rate is next applied; and the resulting value is finally converted into the current value [15]. For example, since the disposal cost will occur in the future at point in time of the construction of a waste repository, the current cost is first estimated at the future time, and then is converted into the present value after applying the appropriate discount rate [16].

The core data for light-water reactor nuclear fuel broadly consists of the initial core, the equilibrium core, and the final core. The criterion of this classification is the difference between withdrawal burnup and enrichment. Thus, the most important variable of the fuel characteristics of an equilibrium core are the number of batches and the withdrawal burnup. The recharging interval can be

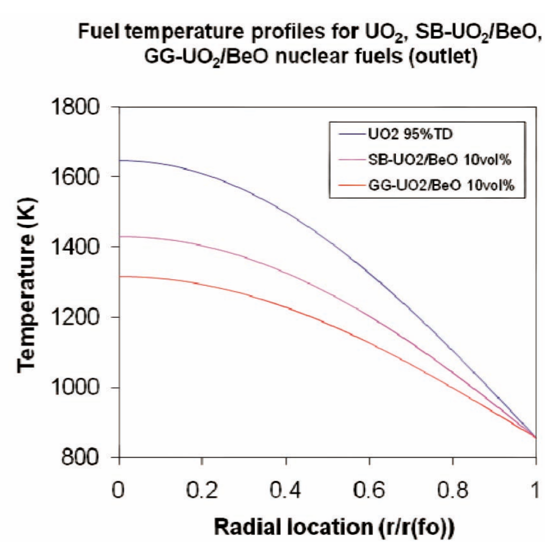

Fig. 4. Fuel Temperature Profiles at Outlet

calculated with these two variables. The numerical equations of nuclear fuel cycle cost calculation are shown in Table 1.

The nuclear fuel cycle cost is calculated by using the BNFCC Version 01 program developed by Purdue University.

3.2 Input Data

In order to calculate the nuclear fuel cycle cost, not only technical data but also economic data are needed. In other words, the base period cost, discount rate, and exchange rate are necessary. Table 2 shows the data for calculating nuclear fuel cycle costs.

4. RESULT OF COST ANALYSIS

In order to analyze the burnup effect on BeO-UO_2 fuel, previous research results are used. According to research results at MIT (Massachusetts Institute of Technology), the relationship of a monotonic increasing function exists between beryllium content and burnup within the limit of fixed burnup when the BeO-UO_2 fuel is loaded in the nuclear reactor. In other words, a linear relationship between beryllium content and burnup exists from 45 MWD/kg of burnup to 85 MWD/kg of burnup [17]. These values result from the assumption that nuclear fuel is appropriately placed in the core.

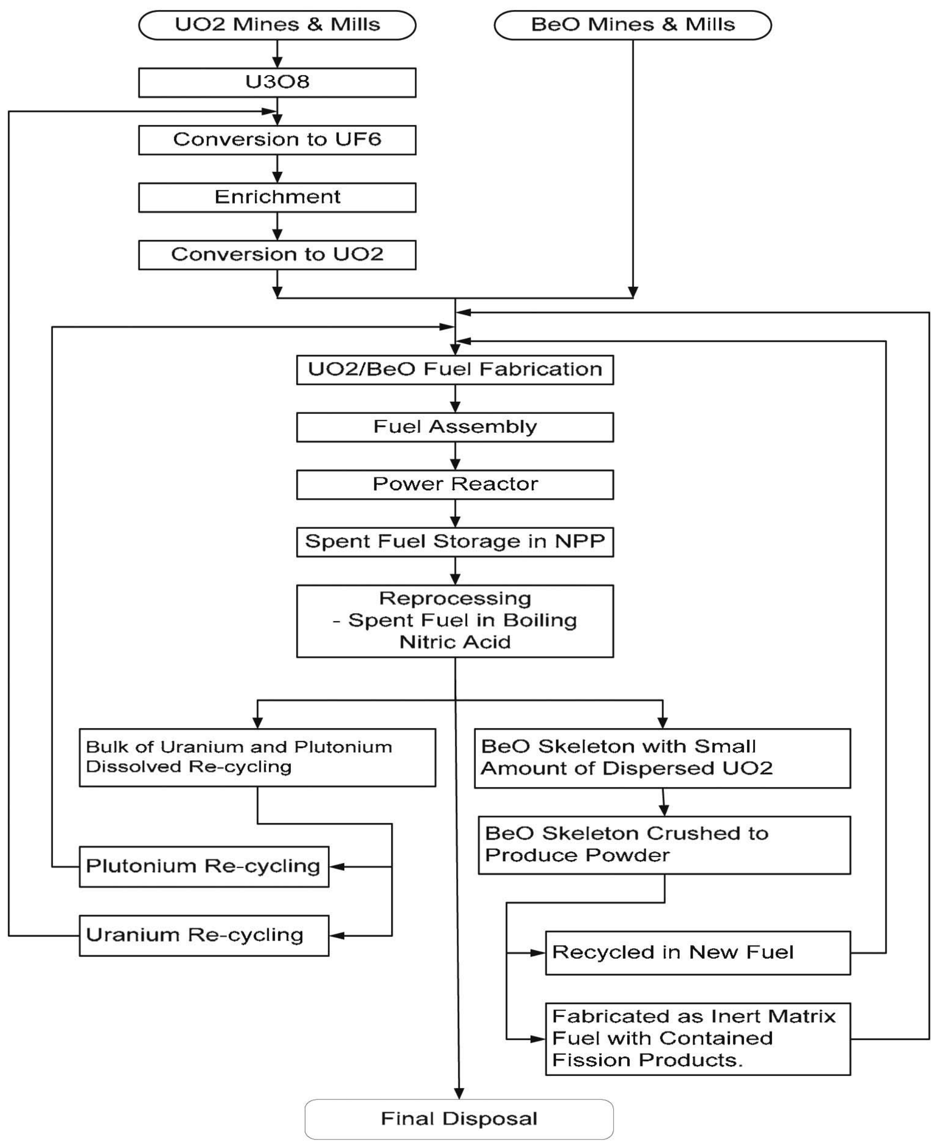

Fig. 5. BeO-UO_2 Matrix Fuel Life Cycle Flow Charts

Table 1. Equations for the Nuclear Fuel Cycle Cost

Category	Equations	
Recharge interval	$R_i = \frac{C_s}{N_b} \times \frac{BUd}{MWt \times L_f \times 365} \quad (Unit : year)$	(2)
Quantity of fabrication	$Qf(t) = \frac{C_s}{N_b}, \quad t = batch$	(3)
Quantity of enrichment	$Qe(t) = [V(EL) + (\frac{EL - T_a}{NAT - T_a} - 1) \cdot V(T_a) - \frac{EL - T_a}{NAT - T_a} V(NAT)]\, Qf(t)\,(1 + LFf)$	(4)
Quantity of conversion	$Qc(t) = \frac{EL - T_a}{NAT - T_a} Qf(t)\,(1 + LFf)$	(5)
Quantity of conversion	$Qu(t) = Qc(t)\,(1 + LFc)$	(6)
Spent fuel generation	$Qsf(t) = Qf(t) \cdot 0.97$	(7)
Cost of Uranium	$Cu = \sum_t \frac{Qu(t) \cdot UCu \cdot (1 + E_u)^{L(t) - LEDu - YRc}}{(1 + D)^{L(t) - LEDu - YRp}}$	(8)
Cost of conversion	$Cc = \sum_t \frac{Qc(t) \cdot UCc \cdot (1 + E_c)^{L(t) - LEDc - YRc}}{(1 + D)^{L(t) - LEDc - YRp}}$	(9)
Cost of conversion	$Ce = \sum_t \frac{Qe(t) \cdot UCe \cdot (1 + E_e)^{L(t) - LEDe - YRc}}{(1 + D)^{L(t) - LEDe - YRp}}$	(10)
Cost of fabrication	$Cf = \sum_t \frac{Qf(t) \cdot UCf \cdot (1 + E_f)^{L(t) - LEDf - YRc}}{(1 + D)^{L(t) - LEDf - YRp}}$	(11)
Cost of transportation ; Applied LAG time	$Ct = \sum_t \frac{Qsf(t) \cdot UCt \cdot (1 + E_t)^{D(t) + LAGt - YRc}}{(1 + D)^{D(t) + LAGt - YRp}}$	(12)
Cost of storage	$Cs = \sum_t \frac{Qsf(t) \cdot UCs \cdot (1 + E_s)^{D(t) + LAGs - YRc}}{(1 + D)^{D(t) + LAGs - YRp}}$	(13)
Cost of disposal	$Cd = \sum_t \frac{Qsf(t) \cdot UCd \cdot (1 + E_d)^{D(t) + LAGd - YRc}}{(1 + D)^{D(t) + LAGd - YRp}}$	(14)
Cost of reprocessing	$Cr = \sum_t \frac{Qsf(t) \cdot UCr \cdot (1 + E_r)^{D(t) + LAGr - YRc}}{(1 + D)^{D(t) + LAGr - YRp}}$	(15)
Cost of Be – credit	$Cbc = \sum_t \frac{Qsf(t) \cdot Sbe \cdot Cbe}{(1 + D)^{D(t) + LAGr - YRp}}$	(16)
Cost of Uranium- credit	$Cuc = \sum_t \frac{Qsf(t) \cdot Ue \cdot Cu}{(1 + D)^{D(t) + LAGr - YRp}}$	(17)
Total cost of direct disposal alternatives	$CTd(t) =$ $Cu(t) + Cc(t) + Ce(t) + Cf(t) + Ct(t) + Cs(t) + Cd(t)$	(18)
Total cost of reprocessing alternatives	$CTr(t) =$ $Cu(t) + Cc(t) + Ce(t) + Cf(t) + Cr(t) - Cbc(t) - Cuc(t)$	(19)

where,
C_s = *Core size*, N_b = *Number of batch*, BU_d = *Burnup*, *MWt* = *Generation*, L_f = *Load Factor*, $L(t)$ = *Loading Time*, $D(t)$ = *Discharging time*, *LED* = *Lead times*, *LAG* = *Lag times Sbe* = Be ratio in spent fule

$$V(x) = (2x - 1)\ln\frac{x}{1 - x},$$

Cbe = (*Cost of Uranium, conversion, enrichment and fabrication for manufacturing of Natual Uranium Fuel* 1 *kg*) – (*Cost of Uranium, conversion and fabrication for manufacturing of BeO – UO2 fuel* 1 *kg*), *Cu* = (*Cost of Uranium, conversion, enrichment and fabrication for manufacturing of Natual Uranium Fuel* 1 *kg*) – (*Cost of conversion, enrichment and fabrication for manufacturing of* Re cov *ered Uranium fuel* 1 *kg*)

The current limit of burnup in Korea and the USA is 60 MWD/kg and 62 MWD/kg, respectively [18, 19]. This paper shows the calculation of the nuclear fuel cycle cost until a burnup of 75 MWD/kg. As a result, when the burnup is 60 MWD/kg and 75 MWD/kg, as shown in Fig. 6, the nuclear fuel cycle cost was about 4.47 Mills/kWh and 3.70 Mills/kWh, respectively. Thus, burnup can be regarded as a factor that greatly affects the nuclear fuel cycle costs.

Table 2. Technical and Economic Data

Economic data	Discount rate		5.0 [% /year]	
	Escalation rate		Category	
	Base year of cost data		Category	
	Unit cost	Direct material cost of BeO and Uranium	BeO: \$317 /kgBeO,U_3O_8: \$64/kgU	
		Conversion	\$8.0/kgU	
		Enrichment	\$100/kgSWU	
		Fabrication	\$250/kgU	
		Transportation	\$50/kgHM	
		Interim storage	\$200/kgHM	
		Reprocessing	\$700/kgHM	
		Final Disposal	\$500/kgU	
Technical data	Reactor	Life time	40 years	
		Thermal power	4020 MWt	
		Electrical power	1390 MWe	
		Load factor	75%	
		Core size	107.91 tU	
	Enrichment data	U-235 content in Natural Uranium	0.7%	
		Enrichment of Feed	0.71 w/o	
		Enrichment of Product	4.6 w/o	
		Enrichment of Tails	0.3 w/o	
	Loss factors	Conversion	0.5 %	
		Fabrication	1.0 %	
		Reprocessing	2.0 %	
	Lead time [unit: months]		Purchase	24
			Conversion	18
			Enrichment	12
			Fabrication	6
	Lag time [unit: months]		Transportation	60
			Reprocessing	72
			Final Disposal	480

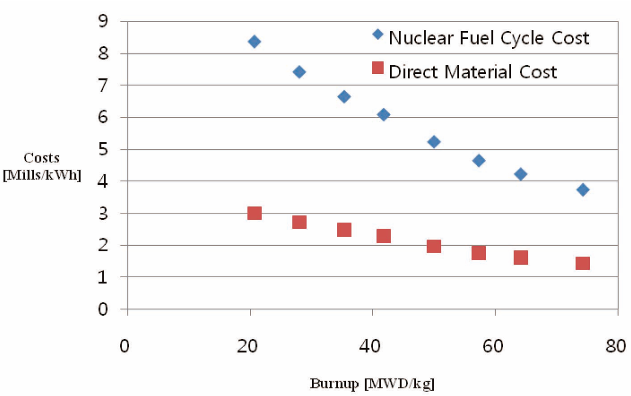

Fig. 6. Nuclear Fuel Cycle Cost as a Function of Burnup

5. CONCLUSIONS

BeO-UO_2 fuel, which can be used in the PWRs, improves the thermal conductivity more than does uranium nuclear fuel, which is used in existing light-water reactors, due to the characteristics of beryllium. This increases the burnup of nuclear fuel and eventually decreases the nuclear fuel cycle costs. These results are produced under the assumption that the beryllium is recycled once.

When burnup is 60 MWD/kg and 75 MWD/kg, the nuclear fuel cycle cost is calculated at 4.47 Mills/kWh and 3.70 Mills/kWh. Therefore, the BeO-UO_2 fuel, the high burnup and the long life cycle of the nuclear fuel create more economic efficiency than exists for current light-water reactor uranium nuclear fuel if the reactor is operated at more than 60 MWD/kg of burnup.

In conclusion, the performance of nuclear BeO-UO_2 fuel, which is currently being developed by Purdue University, is superior to that of existing light-water reactor uranium nuclear fuel in terms of technical safety[10]. As a high burnup and long life cycle nuclear fuel, BeO-UO_2 fuel also has great economic merit since it can decrease the nuclear fuel cycle cost. Therefore, it seems necessary to increase the degree of burnup regulation for existing nuclear fuel for continuous nuclear power generation and economic efficiency improvement of nuclear fuel if BeO-UO_2 fuel is commercialized.

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