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Sensitivity of DUPIC Fuel Fabrication Cost to the use of Fresh Uranium

Won Il Ko, Hangbok Choi and Myung Seung Yang

Korea Atomic Energy Research Institute
P.O. Box 105, Yusong, Taejon, Korea

ABSTRACT

A preliminary conceptual design of a direct use of spent pressurized water reactor (PWR) fuel in Canada deuterium uranium (CANDU) reactors (DUPIC) fuel fabrication plant was studied, which annually converts PWR spent fuel of 400 MTHE into the CANDU fuel. The capital and operating costs were estimated from the viewpoint of conceptual design. Assuming that the annual discount rate is 5% during construction (5 yr) and operation period (40 yr) and contingency is 25% of the capital cost, the levelized unit cost (LUC) of DUPIC fuel fabrication was estimated to be 616 $/kgHE. For new DUPIC fuel option which utilizes fresh uranium to maintain the composition homogeneity, the levelized unit cost of DUPIC fuel fabrication was estimated to be 654 $/kgHE. It should be noted that this study has used representative costs of currently available technologies as the bases of cost estimation. It is recommended that further studies should be performed on other areas such as safety, security, safeguards, process optimization etc

I. Introduction

The DUPIC fuel cycle economics has been an important issue since the initial stage of DUPIC fuel development program. The Korea Atomic Energy Research Institute (KAERI) launched a systematic study[1] of DUPIC fuel cycle economics by parametric analysis. At that time, the unit cost of DUPIC fuel fabrication was regarded as an unknown and the break-even cost of DUPIC fuel fabrication was evaluated by comparing the DUPIC fuel cycle cost with the direct disposal option through parametric analyses. Though the parametric study provided a break-even cost of the DUPIC fuel cycle relative to other fuel cycle options, this "indirect" method contains a high degree of uncertainty because of many assumptions made for the DUPIC fuel fabrication cost. Therefore, an engineering analysis was conducted to derive capital and operating costs through a conceptual design of a DUPIC fuel fabrication plant using the best available technical concept, so that the overall levelized cost could be directly derived.

The preliminary conceptual design analysis for the DUPIC facility was performed by KAERI and

Scientech Inc. in 1995, and then the unit cost of DUPIC fuel manufacturing was estimated from capital cost, operating cost, decommissioning cost, contingency, etc.[2]. The result of the preliminary conceptual design was also reviewed independently by Oak Ridge National Laboratory (ORNL) with a major focus on remote system operation and maintenance[3]. After the preliminary conceptual design and cost analysis, new DUPIC fuel model has been proposed by DUPIC Fuel Cycle Development Team[4~6]. According to the proposed DUPIC fuel model, the existing DUPIC fuel fabrication concept and its cost need to be re-estimated for DUPIC fuel cycle economics.

This paper focuses on the conceptual design and cost estimation of DUPIC fuel fabrication plant along with new DUPIC fuel model. In addition, the cost evaluation also includes sensitivity analyses on the cost parameters such as discount rate and contingency.

II. DUPIC Fuel Composition Adjustment Model

In the DUPIC fuel cycle, spent PWR fuel is directly used in a CANDU reactor after a dry refabrication process. Because there is no separation of isotopes from the spent PWR fuel during the dry refabrication process, DUPIC fuel contains all the actinides and non-volatile fission products, resulting in a high variation in fissile content and isotopic composition depending on the initial and discharge conditions of PWR fuel. Therefore, fuel composition adjustment methods have been previously studied in order to determine the reference DUPIC fuel composition that can be used for the feasibility analysis of the DUPIC fuel in the existing CANDU reactors.

The reference DUPIC fuel models have been evaluated under following requirements:

- The fuel composition variation is minimized.
- The PWR spent fuel utilization is maximized.
- The fresh uranium feed is minimized.
- The DUPIC fuel lattice properties (fuel temperature coefficient, coolant temperature coefficient, moderator temperature coefficient, and coolant void reactivity) are acceptable.
- The DUPIC fuel core performance parameters (maximum channel power, maximum bundle power, and channel power peaking factor) are acceptable.

In principle, it is possible to have a uniform fuel composition if all spent PWR fuels are mixed together. However, mixing all PWR spent fuel in one batch is practically limited and, therefore, a genetic algorithm was developed to search for the optimum combination of PWR spent fuel to obtain the reference fuel composition with a practically acceptable batch size. In fact, various PWR spent fuels can also be used as source material for fuel composition adjustment. A preliminary simulation[6] has shown that it is feasible to achieve the reference fuel composition through rod-wise mixing of PWR spent fuel.

The fissile content of DUPIC fuel can be increased by preferentially using low-burnup PWR spent fuels. In this study, the reference DUPIC fuel model was determined by utilizing 80% of the PWR spent fuel accumulated in Korea by the middle of 1996. When using these PWR spent fuels, it is possible to have the fissile content of 1.57 wt% as the reference DUPIC fuel composition.

On the other hand, it would be more practical at he moment to use fresh uranium to adjust the fuel composition during the fabrication process of the DUPIC fuel. Therefore, a fissile content adjustment method has also been studied as an option to maintain the fuel composition homogenity. In the fissile content adjustment option, the fuel composition is adjusted in two steps. First, two PWR spent fuel assemblies with the highest and lowest ^{239}Pu content are mixed together. This operation is performed three times to reduce variations in the isotopic composition. Secondly, fresh uranium is blended with the PWR spent fuel mixture and the quantity of the fresh uranium is determined such that the ^{239}Pu content is the same for all the mixtures. At the same time, by adjusting the ratio of 3.5 wt% SEU and 0.25 wt% DU in the fresh uranium feed, a unique composition of ^{235}U and ^{239}Pu can be achieved. For this option, the reference fissile content of DUPIC fuel has been determined as 1.0 and 0.45 wt% for ^{235}U and ^{239}Pu, respectively. Under this condition, 96% of PWR spent fuel can be refabricated as DUPIC fuel satisfying the reference fissile content. The amount of SEU and DU used for the composition adjustment are 6.5% and 10.8% of DUPIC fuel on average, respectively.

III. Main Design Requirements of the DUPIC Facility

Overall performance and requirements of the DUPIC fuel facility are described in this section as follows:

1. Plant capacity: The design throughput of the DUPIC facility is 400 MTHE of PWR spent fuel per year, which is roughly equivalent to the fuel need of seven 1000 MWe CANDU reactors.

2. Plant availability: The facility is sized and operated for an average of 70% plant production, which covers allowances for normal process systems startup and shutdown times, scheduled and unscheduled plant equipment maintenance and repair activities, material accountability-related tasks that affect plant operation, and any scheduled plant-wide outage period for major systems refurbishing activities.

3. Plant design life: The design life of the facility is 40 years.

4. Scope of plant: The DUPIC facility is a complete fuel recycle plant that covers all functions and equipment for processing PWR spent fuel and converting it to CANDU DUPIC fuel. The non-fuel components required by the CANDU fuel bundle (e.g., fuel cladding, end caps, spacers, end plates, and dysprosium poison fuel rods) will be fabricated in off-site facilities and shipped to the DUPIC facility. The facility will contain all support systems necessary for DUPIC fuel production.

5. Spent fuel feedstock: The reference feed stock used in the DUPIC facility is standard 17x17 PWR spent fuel assemblies with a burnup level of 35 MWd/kgU and a minimum cooling time of 10 years after discharge from the reactor.

6. DUPIC fuel product: The product of the facility is 43-element CANDU fuel bundles.

7. Fuel storage: The PWR spent fuel receiving and storage system shall accommodate a minimum of three-month operational feed stock capacity (~100 MTHE of spent PWR fuel). The storage and shipping system shall accommodate a minimum of six-week DUPIC fuel production (50 MTHE).

IV. Main Process of DUPIC Fuel Fabrication Facility

The main process building is a rectangular-shaped structure that is located above the ground level. The DUPIC fuel fabrication is performed in the hot cell, which is approximately 85 m in length, 9.75 m in width, and 20 m in height. The cell is separated into dirty and clean areas to prevent the spread of dust-type contamination from the powder processing steps into the fuel pin and assembly fabrication areas where a relatively clean, dust-free, environment is desired. The main DUPIC fuel fabrication process in the hot cell is as follows:

1. PWR spent fuel receiving and storage: The as-received spent fuel is classified by the information (e.g. fissile content) characterized and evaluated by the fuel design data and the burnup characteristics, and stored in the classified area.

2. Disassembly and decladding: The PWR spent fuel rods are removed from the spent fuel structure. The fuel structural hardware is compacted for volume reduction and packaging for off-site disposal. The cladding of the fuel rod is punctured in a controlled environment such that fission gases are collected for waste treatment. The cladding of the fuel rod is sliced longitudinally with a laser or mechanical cutter and spent fuel pellets are removed from the cladding.

3. Fuel oxidation and reduction: The spent fuel pellet fragments and its debris go through three oxidation and reduction processing cycles to get a powder form with suitable characteristics for fuel fabrication. Three conduction ovens are used for each batch of fuel material. These three ovens are arranged in a series and equipped with specially designed automatic material transfer mechanism. The resulting fuel powder is mixed, sampled for size measurement, and assayed for fissile content.

4. Fuel pelletization: Before the powder material is formed into pellets, the powder material is pre-compacted and granulated to increase its flowability. A lubricant (zinc stearate) is added to the powder to facilitate the pelletization process and improve the press tooling life. The powder material is then compacted to a desired density of green pellet. The resulting pellets are stacked onto boats and conveyors for sintering. The sintering step is then conducted to achieve the high pellet density required. After that, the sintered pellets are transferred to the pellet grinding station to achieve the final dimension and surface finish within specification tolerances.

5. Fuel pin fabrication: The fresh fuel cladding and end-cap components processed at off-site are shipped to the DUPIC facility with one end-cap already welded. The stacked fuel pellets are loaded

into the fuel pins and moved to the end-cap welding station. The welded fuel pins are non-destructively tested for weld quality including a helium leak testing. The defective fuel pin is transferred to the scrap material recycle station.

6. Fuel bundle assembly : According to 43-element CANDU fuel bundle design, the DUPIC fuel bundle consists of two different diameter fuel pins. The center fuel pin (the larger size) contains a poison material (dysprosium) mixed with standard natural uranium or spent PWR fuel. The bundle assembly station receives the finished fuel pins from the respective fuel pin fabrication lines and assembles the fuel bundle. The assembled bundles are non-destructively tested for weld quality, dimensions fit, and clearance. Defective fuel bundles are forwarded to the repair station or scrap recycle station. The acceptable fuel bundles are loaded into baskets and storage containers for transfer to the storage or shipping area.

V. Fabrication Cost Estimation of DUPIC Fuel

In this section, the cost of the DUPIC fuel fabrication, which does not utilize any extra uranium for the isotopic composition adjustment of the DUPIC fuel will be addressed. All cost data used in this study are based on the year 1999.

V.A Capital and Operation Cost

The direct and indirect capital costs for reference case were estimated based on previous report[2, 3] and the results are summarized in Table 1. The total direct capital cost was estimated to be 585 M$. The total indirect capital cost is estimated to be 456 M$. Assuming that the contingency is 25% of the total capital cost, the total capital cost for the 400 MTHE/yr facility is estimated to be 1302 M$.

The annual operation and maintenance cost is also summarized in Table 1. The cost for equipment replacement is assumed to be 10% of the total equipment cost, which is equivalent to that of the mean life-time of the process equipment which was established to be 10 years. The process radioactive wastes include vitrified dirty scrap waste (1% of the production capacity) of ~10 m^3, vitrified semi-volatile waste of ~41 m^3, compacted fuel structural material of ~65 m^3, and miscellaneous waste of ~764 m^3. The estimated total annual operation and maintenance cost for the 400 MTHE/yr facility is 155 M$.

The provisions for decontamination and decommissioning of the facility after 40 years design life will be made via an annual sinking fund of 1.25% of the direct capital cost and direct cost portion of the contingency cost for the life of the plant. The decontamination and decommissioning cost is then ~9 M$ per year ((585M$ + 585M$ x 0.25) x 0.0125 =9 M$). The objective of the sinking fund is to provide enough funding to cover the cost of removing all dispersible contamination and reducing fixed contamination to a level that will allow the facility to be used for other purposes.

V.B Unit Cost Model

Life cycle cost (LCC) and levelized unit cost (LUC) models were used for the cost evaluation of DUPIC facility. The net present value (NPV) methodology is used for calculating LCC. The LCC is defined as the total discounted cost necessary to construct, operate, and decommission the DUPIC fuel fabrication facility. Life cycle cost is described by a form of NPV as follows:

$$NPV = \sum_i \frac{C_i}{(1+d)^i} \tag{1}$$

where C_i is the cost in the i-th year, and d means a discount rate. The LUC method will be used to evaluate the fabrication unit cost as follows:

$$LUC = \frac{NPV}{NPB} \tag{2}$$

where the net present benefit is given as

$$NPB = \sum_i \frac{Q_i}{(1+d)^i}\,, \tag{3}$$

and Q_i is the benefit (production amount) to be derived in the i-th year.

Main assumptions for obtaining the life-cycle cost and unit cost are as follow:

- The facility operation period is 2020 ~ 2059 (40 years).

- The facility construction period is 2015 ~ 2019 (5 years).

- The discount rate is 5%.

V.C Unit Cost of DUPIC Fuel Fabrication

A conservative direct capital cost contingency of 25% and a discount rate of 5% are used for the reference model. The input values used for the reference LCC calculation can be found in Table 1. Using the input values and assumptions described in Section V.B, the cost flow of the reference DUPIC facility during life time was made as shown in Fig. 1. From this cost flow, the LCC is estimated to be 7855 M$ in 1999 U.S. dollars. The LCC provides an estimate of the fund required to build, operate, and dispose of the facility during the stated time period (2015-2059) in 1999 U.S. dollars.

In order to determine fuel fabrication unit cost, the LCC must be discounted by an annual factor. This process yields the NPV and provides a reference point for cost comparisons. The calculated reference NPV discounted in the year 1999 is 1594 M$. Once the NPV of the LCC is determined, it is then possible to calculate the LUC. The LUC is determined by dividing the sum of the life cycle discounted cost by the sum of the life cycle discounted production. The LUC of the DUPIC fabrication, which uses only the PWR spent fuel mixing, is 616 \$/kgHE. The cost break-down of the fabrication cost is summarized in Table 2.

VI. Sensitivity Analysis of DUPIC Fuel Fabrication

VI.A Sensitivity of Cost Parameters

The purpose of the sensitivity analysis is to determine the effect of the individual input parameter on the fabrication cost. By performing this analysis, it is also possible to identify which input value has the greatest effect on the final fuel fabrication cost. As the DUPIC design process continues, the value identified to have the greatest impact on the fuel fabrication cost can undergo further detailed analysis to determine final DUPIC fabrication cost more accurately.

The discount rate, production capacity and contingency were chosen as items of the sensitivity analysis. The fabrication cost was estimated for the cost parameter ranging from 50% to 150% of the reference value, and the results are shown in Fig. 2.

For sensitivity analysis of production capacity, the power factor method based on reference capacity was used, instead of designing the facility with a new capacity. The power factor (f) will be applied to the following equation:

$$\text{Cost for a capacity} = \text{cost for base capacity} \times (\text{capacity} / \text{base capacity})^{f} \qquad (4)$$

where the powder factor is determined by engineering judgement. In this study, the power factors are assumed to be 0.1 for site preparation, 0.6 for process systems, 0.6 for main processing building, 0.3 for site support facilities, 0.4 for staffs, 0.7 for utilities, 1.0 for materials, 0.6 for equipment replacement and 1.0 for radwaste disposal.

The results have shown that the contingency factor has relatively small effect on the unit cost of production while the variations in production volume have the most significant impact on the unit cost. The discount rate change from 2.5 to 6.25% and the production volume change from 200 to 500 MTHE create the unit cost variation of 26 and 33%, respectively.

Since variations in the contingency factor have little impact, conservatism is warranted. To a lesser degree, the same argument holds for the discount rate. Since production capacity has the greatest impact on the cost, the anticipated facility throughput is the primary component for the determination of the cost effectiveness for the DUPIC fuel fabrication facility.

VI.B Effect of Fresh Uranium on Fabrication Cost

DUPIC fuel composition changes depending on initial enrichment, discharge burnup, and specific power of the PWR fuel. In order to resolve the fuel composition heterogeneity, the composition adjustment method has been proposed as described in Chapter II. In this section, the effects of adding extra uranium during DUPIC fuel fabrication process on fabrication cost are examined. For this, the following approaches and assumptions are used:

- The amount of slightly enriched uranium (SEU) or natural uranium is estimated; then, the cost of SEU or natural uranium is evaluated.
- The cost of SEU or natural uranium is included in the fabrication cost as the operation and maintenance cost.

For the cost estimation of SEU to be added, uranium, conversion and enrichment costs are needed. The SEU cost ultimately becomes the sum of the uranium, conversion and enrichment cost. The enrichment cost is calculated with Separative Work Unit (SWU) concept as follows:

$$\text{SWU} = M_p V_p + M_t V_t - M_f V_f \tag{5}$$

where M_p = mass of enriched uranium to be charged in the DUPIC facility,
M_f = mass of natural uranium feed in enrichment plant, and
M_t = mass of depleted uranium discharged from the enrichment plant.

$$V_x = (2e_x - 1)\ln\frac{e_x}{(1-e_x)} \tag{6}$$

and x is subscript for f, p or t,
where e_p = fraction of ^{235}U of uranium to be charged in the DUPIC plant (3.5 wt% in this study),
e_f = fraction of ^{235}U in the uranium feed (0.711 wt% in this study), and
e_t = fraction of ^{235}U in the tails (0.25 wt% in this study).

Then, $$M_f = M_p \frac{(e_p - e_t)}{(e_f - e_t)} \tag{7}$$

and $$M_t = M_f - M_p \tag{8}$$

From above equations, if M_p (mass of uranium to be charged in the DUPIC plant) and three fractions of the ^{235}U in enrichment plant are known, the SWU can be calculated.

For uranium, conversion and enrichment cost, OECD/NEA report[7], which studied world-wide nuclear fuel cycle costs in 1993, and 2000 NUKEM market report[8], are referred in this study. In the OECD/NEA report, the reference uranium cost is 50 \$/kgU and the reference conversion and enrichment costs are 8 \$/kgU and 110 \$/kgU, respectively. In the 2000 NUKEM market report, however, these costs have been decreased. Therefore the cost in the OECD/NEA report is used as the maximum, while the cost in the 2000 NUKEM market report is used as the minimum in this study.

Table 3 shows the ranges of the costs and cited references used for estimating SEU and natural uranium cost, which will be included in DUPIC fuel fabrication cost.

The results of the sensitivity analysis for adding uranium are shown in Tables 4 and 5 for natural uranium and SEU, respectively. As shown in Table 4, adding natural uranium during DUPIC fuel fabrication process shows only a slight increase of the fabrication unit cost. Even though natural uranium is added to the spent fuel powder by 50%, the fabrication unit cost shows an increase of only 4.1%, from 616 to 641 \$/kgU. However, Table 5 shows that adding enriched uranium has more effect on the fabrication unit cost. A 10% addition of enriched uranium causes ~9.6% increase in the fabrication unit cost, from 616 to 675 \$/kgU. As results, the levelized unit cost of DUPIC fuel fabrication, that uses freshed uranium for the fissile content adjustment, was estimated to be 654 \$/kgHE.

VII. Conclusions and Recommendations

Since the initial technical feasibility study on the DUPIC process, significant interests have been drawn to the economics of the DUPIC fuel cycle. For this reason, a preliminary conceptual design of a DUPIC fuel fabrication plant was studied, which annually converts spent PWR fuel of 400 MTHE into CANDU fuel. The LUC of DUPIC fuel fabrication was estimated to be 616 \$/kgHE as of December, 1999. The sensitivity calculation of the LUC has shown that the production capacity of the DUPIC fuel facility has the greatest impact on the cost. For DUPIC fuel option that utilizes fresh uranium to maintain the composition homogeneity, the LUC of DUPIC fuel fabrication was estimated to be 654 \$/kgHE. This study has used representative costs of currently available technologies as the bases for cost estimation. It should also be noted that the conceptual design and cost information contained in this study was extracted from the public domain and general open literature. It is recommended that further studies should be performed on other important areas such as safety, security, safeguards, process optimization, etc.

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Table 1 Life Cycle Cost Estimation

(Price Basis year : Dec. 1999)

Content	Sub-content	Cost(k$)
Capital Cost	Direct cost	585,141
	· Site preparation	12,592
	· Process systems	328,641
	· Main processing building	204,430
	· Site support facilities	39,478
	Indirect cost	456,411
	Contingency	260,388
	Total	1,301,941
Operation & Maintenance Cost (annual basis)	Staff	23,993
	Utilities	10,102
	Materials	22,339
	Equipment replacement	23,405
	Radwaste disposal	74,851
	Total	154,690
Decommissioning Cost (annual basis)	Decommissioning cost	9,143

Table 2 Estimated Costs for DUPIC Fuel Fabrication Plant of 400 MTHE/yr Capacity

Item		NPV (M$)	Fraction of Levelized Unit Cost
Capital Life Cycle Cost	Direct Costs	198	*33.6 %*
	Indirect Costs	155	
	Contingency	88	
Operation and Maintenance Costs (annual basis)	Staff	129	*62.7 %*
	Utilities	53	
	Materials	117	
	Equipment Replacement	124	
	Process Waste Disposal	400	
Decontamination and Decommissioning Life Cycle Cost		49	*3.7 %*
40-years Life Cycle Cost (M$) in Net Present Value		1,594	
Levelized Unit Cost ($/kgHE)		***616***	

Table 3 Ranges of Uranium, Conversion and Enrichment Costs

Items		Costs	References
Minimum values	Uranium	14.66 \$/lbU_3O_8 38.12 \$/kgU	Average EURATOM medium and long term prices (2000 NUKEM report[8])
	Conversion	3.2 \$/kgU	Spot Conversion price (2000 NUKEM report[8])
	Enrichment	80 \$/SWU	Separative work spot price (2000 NUKEM report[8])
Maximum values	Uranium	19.2 \$/lbU_3O_8 50 \$/kgU	Reference value used in OECD/NEA report[7]
	Conversion	8 \$/kgU	
	Enrichment	110 \$/SWU	

Table 4 Sensitivity Analysis for Adding Natural Uranium

Natural uranium fraction (wt%)	Annual natural uranium feed (MTU)	Annual natural uranium cost (k\$)		Fabrication cost (\$/kgHM)	
		Minimum*	Maximum**	Minimum*	Maximum**
5	20	762	1,000	618	619
10	40	1,525	2,000	620	621
15	60	2,287	3,000	622	624
20	80	3,050	4,000	624	626
25	100	3,812	5,000	626	629
30	120	4,574	6,000	628	631
35	140	5,337	7,000	629	634
40	160	6,099	8,000	631	636
45	180	6,862	9,000	633	639
50	200	7,624	10,000	635	641

*Uranium cost is 38.12\$/kgU.

**Uranium cost is 50 \$/kgU.

Table 5 Sensitivity Analysis for Adding Slightly Enriched Uranium

SEU fraction (wt%)	Annual SEU feed (MTU)	Annual SEU cost (k$)		Fabrication cost ($/kgHM)	
		Minimum*	Maximum**	Minimum*	Maximum**
1	4	1705	2349	620	622
2	8	3410	4698	625	628
3	12	5114	7046	629	634
4	16	6819	9395	633	640
5	20	8524	11744	637	645
6	24	10229	14093	642	651
7	28	11933	16422	646	657
8	32	13638	18790	650	663
9	36	15343	21139	654	669
10	40	17048	23488	659	675

* A case for uranium cost of 38.12 $/kgU, conversion cost of 3.2 $/kgU and enrichment cost of 80 $/SWU.

** A case for uranium cost of 50 $/kgU, conversion cost of 8 $/kgU and enrichment cost of 110 $/SWU.

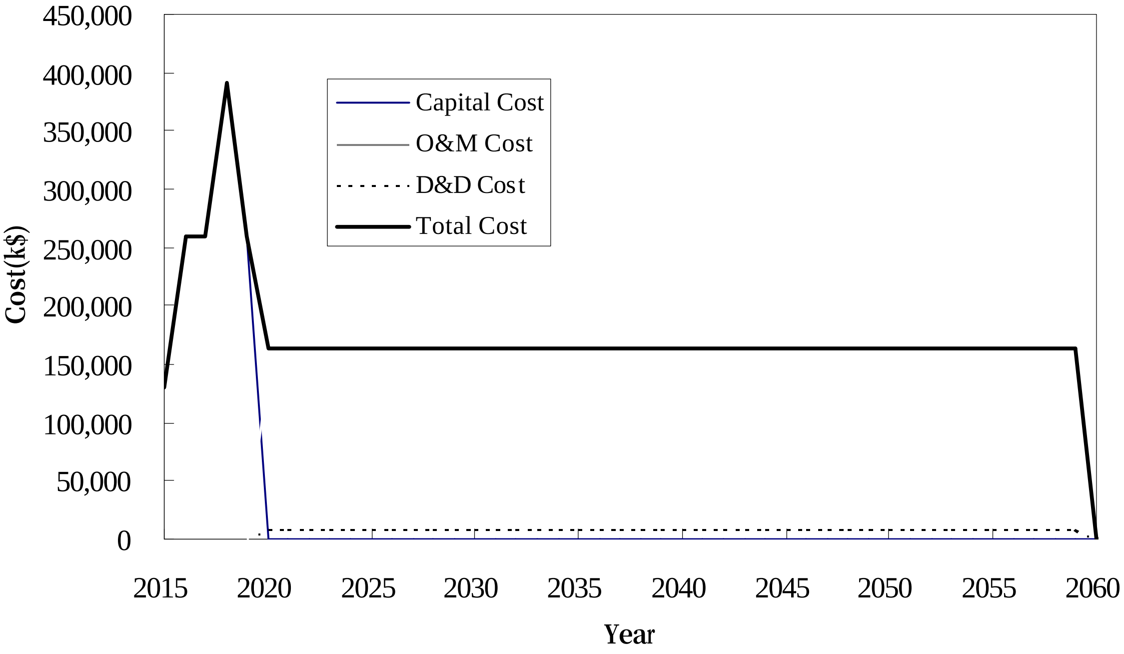

Fig. 1 Cost Flow of DUPIC Fuel Fabrication Facility

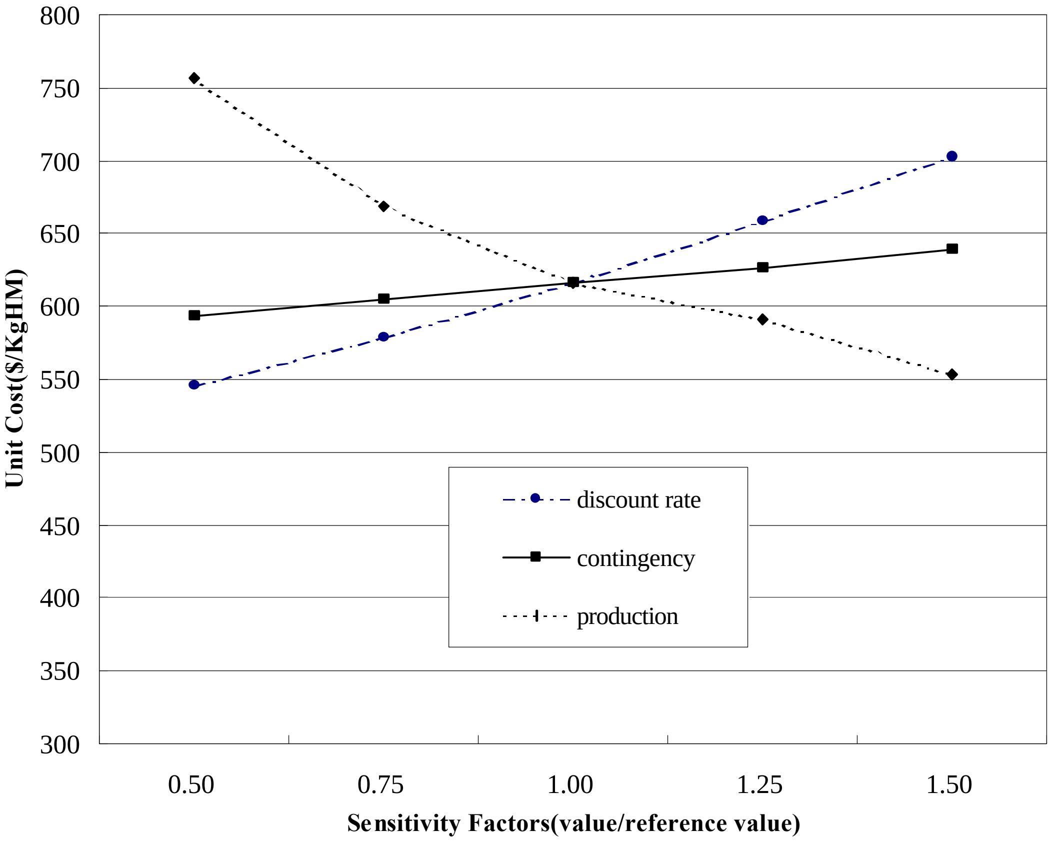

Fig. 2 Sensitivity of Cost Parameters