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# REACTIVITY CONTROL OPTION FOR DUPIC FUEL BY NATURAL URANIUM

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## ABSTRACT

In DUPIC fuel cycle, the spent pressurized water reactor (PWR) fuel is refabricated as a DUPIC fuel by a dry process. However, because the spent PWR fuel composition depends on the initial enrichment and burnup condition of the PWR fuel, the composition of a DUPIC fuel is not uniquely defined. Therefore, the composition adjustment methods of DUPIC fuel have been studied for the purpose of reducing the effects of composition heterogeneity on core performance parameters. This study focuses on the reactivity control method which uses natural uranium feed to minimize the effect on the manufacturing cost of DUPIC fuel when adjusting the excess reactivity of spent PWR fuel. The results of this study have shown that the reactivity of DUPIC fuel can be controlled tightly by feeding natural uranium to the spent PWR fuel mixture. However, the advantage of using natural uranium to reduce the manufacturing cost is relatively small considering the fuel cycle cost penalty caused by the discharge burnup decrease.

## I. INTRODUCTION

A synergistics fuel cycle between PWR and CANDU, named a DUPIC fuel cycle,[1] provides excellent resource utilization, spent fuel reduction and safeguardability. However, because there is no separation of isotopes from spent PWR fuel during the refabrication process, the DUPIC fuel contains all the actinides and fission products, which results in a higher fissile content and isotopic composition change depending on the initial and discharge conditions of PWR fuels. The fissile content and heterogeneity of the fuel composition introduce complexities when the DUPIC fuel is actually implemented in a CANDU reactor which adopts an on-power refueling scheme because the operational flexibility is reduced if fuels of higher fissile content with different compositions are loaded throughout the core.

For a CANDU reactor loaded with the DUPIC fuel, the effect of a higher fissile content on core performances is accommodated to a certain extent by changing the fuel management scheme.[2] In other words, the number of fuel bundles loaded per refueling operation will be smaller for a DUPIC fuel core compared with that of a natural uranium core in order to control the excess reactivity provided by the DUPIC fuel. On the other hand, in a nuclear plant, operators select refueling channels based on power distribution and burnup history, assuming that the nuclear

characteristics of fresh fuels are the same. In order to facilitate such a practice, it is necessary to adjust the DUPIC fuel composition to reduce the uncertainty in core characteristics and achieve a large enough operation margin. However, the adjustment of an individual isotopic concentration is not practical for the spent PWR fuel which has all actinides and fission products. Even for the major fissile isotopes like $^{235}U$ and $^{239}Pu$, an adjustment of the fuel composition using extra plutonium is not appropriate because of political restrictions.

Therefore three options to reduce the fuel composition heterogeneity have been proposed, which are:

- adjustment of major fissile content using slightly enriched uranium (SEU) and depleted uranium (DU),
- reactivity control by natural uranium, and
- combination of spent PWR fuels by partial mixing.

The first option[3] has already been studied extensively and the third option is under investigation separately. However, for the first option, there is a cost rise for the DUPIC fuel manufacturing because of using SEU to adjust the fissile content and, therefore, it has also been suggested to investigate the possibility of using natural uranium so that the fuel manufacturing cost is saved. In this study, we have studied the potential of using natural uranium to control the reactivity of a DUPIC fuel and compared results with those of the first option.

## II. REVIEW OF FISSILE CONTENT ADJUSTMENT OPTION

If a fuel bundle with different neutronic property is loaded in a core, it is expected that the local power fluctuation becomes worse, even though the reactivity control system is working properly and, therefore, it has been recommended that the neutronic property of a DUPIC fuel be made as uniform as possible in order to minimize the influence of the fuel composition heterogeneity on reactor operation. In the fissile content adjustment option, the fuel composition is adjusted in two steps. First, a few spent PWR fuel assemblies are mixed together to reduce variations in isotopic composition. This operation will reduce the variation of most isotopic concentrations, depending on how the mixing assemblies are chosen. Here, the mixing assemblies are chosen such that the variation of $^{239}Pu$ is reduced. However, because the mixing operation does not produce a unique composition of any isotope in the fuel, the fresh uranium is blended secondly. By adjusting the $^{235}U$ concentration in the fresh uranium (SEU and DU), a unique composition of $^{235}U$ and $^{239}Pu$ can be achieved.

The reference fissile contents of the DUPIC fuel have been determined to be 1.0 wt% $^{235}U$ and 0.45 wt% $^{239}Pu$. Due to the limitation in enrichment of feed uranium (3.5 wt% and 0.25 wt% for SEU and DU, respectively), not all spent PWR fuels satisfy the target enrichments of $^{235}U$ and $^{239}Pu$, which is expressed in terms of spent PWR fuel utilization factor as shown in Table I along with the amount of the fresh uranium feed. It can be seen that a very high utilization factor can be obtained if the mixing operation is taken three times. At the same time, the amount of SEU feed is getting smaller as the number of mixing increases, meaning that the fissile content adjustment is more advantageous if spent PWR fuels are mixed many times.

Table I. Characteristics of Fissile Content Control Option

| | First Mixing | Second Mixing | Third Mixing |
|---|---|---|---|
| Number of Assemblies Mixed | 2 | 4 | 8 |
| Spent PWR Fuel Utilization (%) | 90 | 90 | 96 |
| Amount of SEU Feed (%) | 9.5 | 8.8 | 7.9 |
| Amount of DU Feed (%) | 11.7 | 12.2 | 13.1 |

Though the contents of $^{235}U$ and $^{239}Pu$ are tightly controlled, other isotopes still have composition variations, which can be seen in terms of an infinite multiplication factor (or reactivity for convenience). Fig. 1 shows the variation of reactivity distribution after each mixing operation. Though all the DUPIC fuel satisfy the reference fissile content, the variation of reactivity is reduced and the distribution becomes symmetric as the number of mixing operation increases. In general, if the plutonium content is high, so is the fission products content. Therefore it can be interpreted that the mixing operation based on plutonium content contributes to the homogenization of fission products too.

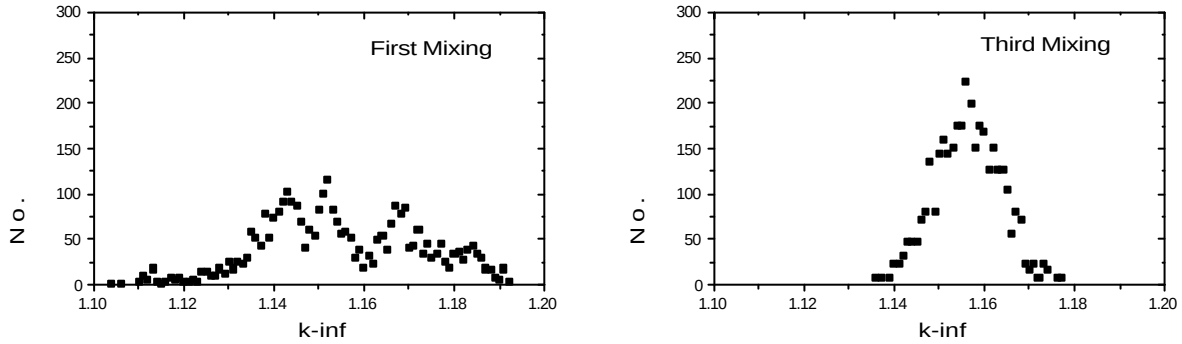


Fig.1 Distribution of $k_\infty$ for Fissile Content Adjustment

## III. REACTIVITY CONTROL OPTION

In this option, the reactivity of a DUPIC fuel lattice is used as a target variable of the fuel composition heterogeneity control. The reactivity is an integral parameter that represents nuclear characteristics of a fuel in a reactor system. A basic assumption of the fuel composition heterogeneity control is that the adjusted quantity should be measurable. For example, contents of $^{235}U$ and $^{239}Pu$ can be measured by either chemical analysis or non-destructive assay for the fissile content adjustment option. In case of the reactivity control, the subcriticality of the DUPIC fuel powder could be counted by neutron multiplicity[4] or delayed neutron measurement.[5]

### III.1 Spent PWR Fuel Mixing

In the reactivity control option, as was done for the fissile content adjustment option, the spent PWR fuels of the highest and lowest reactivity are mixed together at first so that the overall reactivity variation is reduced. Secondly the excess reactivity is controlled by adding natural uranium. Fig. 2 shows the distribution of reactivity for all spent PWR fuels in the CANDU

environment. It can be seen that about 90% of the spent PWR fuels are located in the linearly varying region of the $k_\infty$. About 25% of the fuels have $k_\infty$'s which are even lower than that of natural uranium fuel (1.11681) while about 7% of the spent PWR fuels have extremely high reactivity (>1.25811). Fig. 3 shows how the distribution of reactivity changes as the number of spent PWR fuel mixing increases before natural uranium is added. After the third mixing operation, the reactivity of about half of spent PWR fuels fall in $1.166 \pm 0.001$. It is worth noting that some fuels still have high reactivity even after the third mixing operation. They are mostly defected fuels which have relatively large amount of $^{235}U$ and a small amount of fission products. Therefore most of natural uranium feed is used to reduce reactivity of those spent PWR fuels. However this also indicates that further reduction in natural uranium feed is expected if the spent PWR fuels are chosen selectively for the mixing operation.

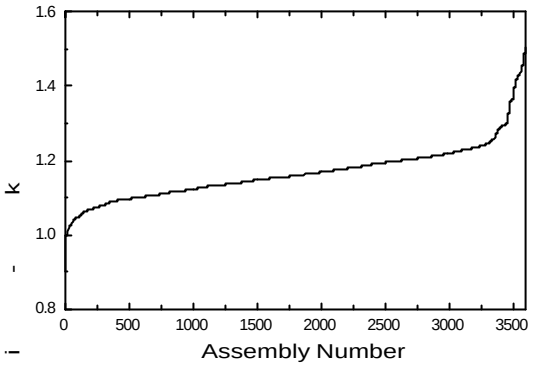


Fig. 2 Distribution of $k_\infty$

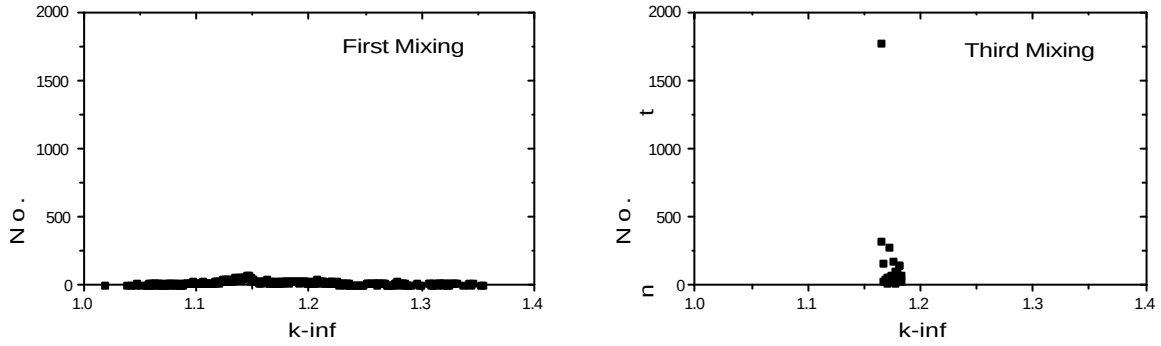


Fig. 3 Distribution of $k_\infty$ for Reactivity Control (before adding natural uranium)

## II.2 Reactivity Control By Natural Uranium

By adding natural uranium to spent PWR fuel mixture, it is possible to have fuels of uniform reactivity. However, because the reactivity of natural uranium fuel is fixed (1.11681 at fresh clean condition), it is possible to adjust the spent PWR fuel reactivity when it is higher than that of natural uranium fuel. This means that some of spent PWR fuels can not be used for reactivity control if no mixing operation is taken. When the mixing operation is performed, the amount of spent PWR fuels accepted for the reactivity control will depend on the lowest (target) reactivity. As shown in Fig. 4, the lowest reactivity increases as the number of mixing increases under the condition that 100% of spent PWR fuels are utilized. However, a full use of spent PWR fuels requires to use a large amount of natural uranium feed

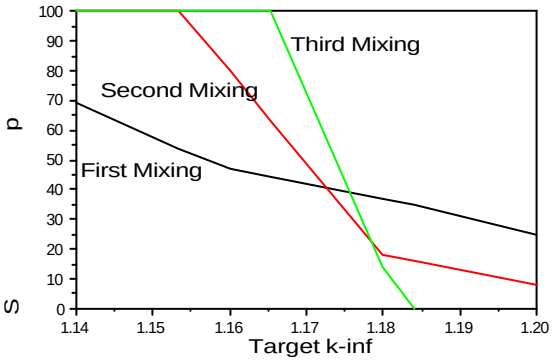


Fig. 4 Spent PWR Fuel Utilization

and reduces the fuel discharge burnup in a CANDU reactor. Fig. 5 shows the amount of natural uranium feed after the third mixing operation.

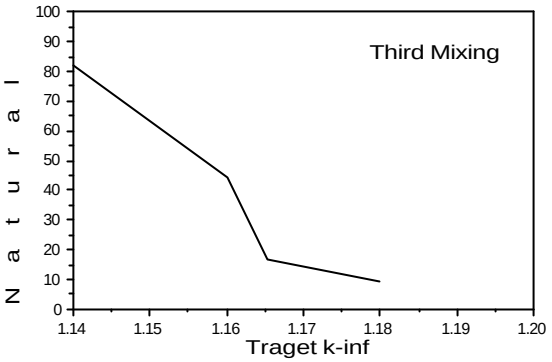


Fig. 5 Amount of Natural Uranium Feed

III.3 Utilization of High Reactivity Fuel

In order to increase the discharge burnup, the spent PWR fuels of high reactivity have been chosen for the mixing operations. As was done before, natural uranium is blended after the third mixing operation to satisfy the target reactivity and natural dysprosium is added to the center rod only to suppress the void reactivity. The characteristics of the DUPIC fuel is summarized in Table II for the selected spent PWR fuel utilization factors. It can be seen that the discharge burnup increases as the utilization factor decreases. However the amount of natural uranium feed is not changing monotonically, which is attributed to the asymmetric distribution of high reactivity fuels. In order to estimate the fuel cycle cost, the manufacturing cost of DUPIC fuel was calculated by including the cost of natural uranium feed in the operation and maintenance cost. It can be seen in Table II that the manufacturing cost does not change much from the reference value (558$/kgU) and the fuel cycle cost is mostly affected by the discharge burnup.

Table II. Summary for Utilization of High Reactivity Fuels

| | Utilization Factor of Spent PWR Fuel | | | | |
|---|---|---|---|---|---|
| | 90 | 80 | 70 | 60 | 50 |
| Target $k_\infty$ | 1.17178 | 1.18189 | 1.19118 | 1.20184 | 1.21421 |
| Average $k_\infty$ | 1.17240 | 1.18254 | 1.19185 | 1.20256 | 1.21485 |
| Natural uranium fraction (wt%) | 27.9 | 25.9 | 26.6 | 25.4 | 22.0 |
| Dysprosium in center rod (wt%) | 3.71 | 3.92 | 4.02 | 4.20 | 4.53 |
| Discharge burnup (MWd/T) | 11869 | 12799 | 13539 | 14500 | 15854 |
| Annual natural uranium feed (MTU) - 400 T/year capacity | 112 | 104 | 106 | 102 | 88 |
| Annual natural uranium cost (k$)* - O&M cost | 5580 | 5180 | 5320 | 5080 | 4400 |
| Manufacturing cost ($/kgU) | 572 | 571 | 571 | 571 | 569 |
| Fuel cycle cost (mills/kWh) | 5.79 | 5.65 | 5.54 | 5.41 | 5.24 |

* $U_3O_8$ : 50$/kgU

## IV. COMPARISON OF COMPOSITION ADJUSTMENT OPTIONS

It is obvious that the reactivity of a DUPIC fuel is not controlled tightly for the fissile content adjustment option while the fissile content is not tightly controlled for the reactivity control option. Distributions of reactivity and major isotopic contents are compared in Table III with their percentile

variation ($2\sigma$) after the third mixing operation. For the fissile content adjustment, variations of isotopic contents are relatively small because amounts of transuranics and fission products are proportional to the $^{239}Pu$ content for the irradiated fuel and their distribution is also narrowed when spent PWR fuels are mixed such that the $^{239}Pu$ variation is reduced. On the other hand, for the reactivity control, the composition variation is relatively large except $^{235}U$, which means that the reactivity is strongly dependent on the $^{235}U$ content. The relatively large variation of transuranics and fission products content is due to the spent PWR fuel of high reactivity which requires a large amount of natural uranium feed to have a uniform reactivity.

Table III. Comparison of $k_\infty$ and Isotopic Content Distributions

| Isotope | | Fissile Content Adjustment | | Reactivity Control* | |
|---|---|---|---|---|---|
| $k_\infty$ | | 1.15623 | ±0.63% | 1.17240+ | ±0.02% |
| Actinides | $^{235}U$ | 10000.0 | ±0.1% | 8707.3 | ±4.6% |
| | $^{239}Pu$ | 4500.0 | ±0.1% | 3939.1 | ±36.6% |
| | $^{241}Pu$ | 423.7 | ±6.7% | 365.4 | ±39.9% |
| | $^{240}Pu$ | 1758.9 | ±4.1% | 1508.3 | ±37.9% |
| | $^{241}Am$ | 617.1 | ±5.1% | 528.7 | ±38.2% |
| Fission Products | $^{155}Gd$ | 8.8 | ±8.3% | 7.3 | ±38.1% |
| | $^{149}Sm$ | 3.3 | ±0.7% | 2.9 | ±36.2% |
| | $^{143}Nd$ | 608.6 | ±3.0% | 527.4 | ±37.8% |
| | $^{151}Sm$ | 10.3 | ±2.6% | 8.9 | ±36.9% |
| | $^{103}Rh$ | 318.6 | ±3.9% | 274.0 | ±38.1% |

*Spent PWR fuel utilization : 90% for high reactivity fuels
+Dysprosium is not included yet.

Table IV shows typical lattice properties of the DUPIC and natural uranium fuel. Note that the void reactivity of the DUPIC fuel is smaller than that of natural uranium fuel at equilibrium burnup because a poison material is blended in the DUPIC fuel. For DUPIC fuels of fissile content adjustment and reactivity control, nuclear properties are similar for typical reactivity coefficients. However, the burnup penalty is relatively large if the reactivity is controlled because excess reactivity was lost when the spent PWR fuels are mixed with natural uranium.

Table IV. Comparison of Lattice Property

| | Fissile Content Adjustment | | Reactivity Control | | Natural Uranium | |
|---|---|---|---|---|---|---|
| | Fresh | Equil | Fresh | Equil | Fresh | Equil |
| Void reactivity(mk) | 9.3 | 11.8 | 9.7 | 11.9 | 16.7 | 14.0 |
| Fuel temp. coeff.($\mu$k/K) | -4.1 | -1.4 | -3.7 | -1.2 | -10.9 | 0.5 |
| Coolant temp. coeff.($\mu$k/K) | 33.2 | 48.2 | 35.3 | 49.3 | 31.7 | 53.9 |
| Discharge burnup | 14886 MWd/T | | 11869 MWd/T | | 7228 MWd/T | |

## V. CONCLUSION

This study has shown that the heterogeneity of DUPIC fuel represented either by fissile content or reactivity can be reduced appreciably either by adjusting fissile content directly or the reactivity. Because the fissile content adjustment provides a unique value of uranium to plutonium ratio, it is expected that those fuels have similar burnup behavior, which is considered as an advantage in fuel management of a DUPIC core. However, because SEU is used to adjust the fissile content, there is a certain amount of penalty in DUPIC fuel fabrication cost, which will eventually increase the overall DUPIC fuel cycle cost. On the other hand, the reactivity control option provides an excellent control on DUPIC fuel initial reactivity, which is an advantage especially for an on-power refueling reactor like CANDU. The use of natural uranium feed will introduce only a small DUPIC fuel manufacturing cost increase. However, the burnup penalty of the DUPIC fuel caused by feeding natural uranium will be a drawback to the fuel cycle cost.

**Acknowledgement**

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