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# STATISTICAL ANALYSIS OF DUPIC FUEL COMPOSITION HETEROGENEITY

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## ABSTRACT

*The fuel composition heterogeneity effect on reactor performance parameters was assessed by refueling simulations for the reference DUPIC fuel model. The refueling simulation was performed using 30 heterogeneous fuel types which were determined by the agglomerative hierarchical clustering method. The heterogeneity effect was considered during the refueling simulation by randomly selecting fuel types for the refueling operation. The refueling simulations of the heterogeneous core have shown that the key performance parameters are close to those of the core that has single fuel type. The uncertainties of the maximum channel power, maximum bundle power, and channel power peaking factor due to the fuel composition heterogeneity are 0.5, 0.7, and 0.8%, respectively, including the uncertainty of the group-average fuel property. This study has shown that the reference DUPIC fuel option reduces the composition heterogeneity effectively and the zone controller unit has a sufficient margin to adjust the perturbations caused by the fuel composition heterogeneity.*

## I. INTRODUCTION

The direct use of spent pressurized water reactor (PWR) fuel in the Canada deuterium uranium (CANDU) reactor is collectively referred to as the DUPIC fuel cycle.[1] In the DUPIC fuel cycle, however, the direct refabrication of spent PWR fuel to CANDU fuels results in heterogeneous fuel composition, depending on the enrichment, irradiation history, and discharge burnup of PWR fuels. If the fuels with different compositions are loaded during the on-power refueling of a CANDU reactor, it is expected that the channel and bundle powers upon refueling are unpredictable because the fresh fuel composition changes whenever the refueling operation is performed. Therefore, extensive studies[2,3] have been performed to reduce the DUPIC fuel composition heterogeneity in CANDU reactors. As a result, the reference DUPIC fuel model was determined such that the fissile content is adjusted tightly using slightly enriched uranium (SEU) and depleted uranium (DU) feed material. Though this option effectively reduces the heterogeneity of the DUPIC fuel, there is a residual heterogeneity in the fuel composition, which could affect the core performance parameters. The objective of this study is to estimate the uncertainty level of core performance parameters statistically by performing refueling simulations using the heterogeneous fuel types randomly loaded in the core.

However, a direct introduction of the heterogeneous fuel types into the diffusion calculation is not generally allowed due to the system size and complexity,[4] so that a specific method is necessary to reduce the size and simplify the system. For the DUPIC fuel composition heterogeneity control study, about 3600 spent PWR fuel assemblies are considered initially, and inter-assembly mixing operations are performed in order to reduce the composition heterogeneity. Even though the inter-assembly mixing operations are performed three times, the number of distinct fuel types is still more than 400, which is too many to be handled by the core simulation code. Therefore, an agglomerative hierarchical clustering (AHC)[5] technique was applied in order to reduce the problem size. Then, the fuel composition heterogeneity effect on the core performance parameters is estimated by randomly assigning the fuel type for the refueling simulation.

## II. REFERENCE DUPIC FUEL MODEL

The target of the fissile content adjustment is to produce spent PWR fuel powder which has fixed contents of major fissile isotopes $^{235}$U and $^{239}$Pu. For this end, the spent PWR fuels of the highest and the lowest $^{239}$Pu content are mixed. The mixing operation is performed three times so that overall isotopic variation is reduced. Then, fresh uranium (3.5 wt% SEU and 0.25 wt% DU) is added to the spent PWR fuel mixture to fix the $^{235}$U and $^{239}$Pu content by adjusting the ratio of SEU and DU feed. Based on the sensitivity calculations for the lattice and core performance parameters,[2] the target contents of $^{235}$U and $^{239}$Pu were determined as 1.0 and 0.45 wt%, respectively. Though the major fissile contents are fixed, other actinides and fission products have variations in isotopic contents. Such a heterogeneity in the fuel composition can be represented by an integral parameter such as an infinite multiplication factor. The distribution of $k_\infty$ for the fissile-content-adjusted DUPIC fuel is shown in Fig. 1. Though about 3600 spent PWR fuel assemblies were used initially, there are 450 distinct fuel types because the mixing operation was performed three times.

## III. HETEROGENEITY ANALYSIS BY REFUELING SIMULATION

The effect of fuel composition heterogeneity on the core performance can be estimated by the refueling simulation. But, if all different fuel types are modelled in the refueling simulation, the simulation will be very expensive because all the lattice parameters should be generated before-hand and the capacity of the simulation program needs to be expanded enormously, which is impractical to estimate the heterogeneity effect. Therefore, a clustering technique was introduced to reduce the number of distinct fuel types without losing physical importance of them. During clustering, the fuel types of similar neutronic properties (e.g., $k_\infty$) are regarded as the same fuel type. By doing this, the number of distinct fuel types is reduced and the computing effort for the analysis of heterogeneity effect can be lightened appreciably.

### III.A. Number of Fuel Types

The sensitivity of the clustering group to core performance parameters was assessed for the instantaneous core by changing the number of fuel types. The number of clustering groups considered are 1, 10, 15, 20, 25 and 30. Currently, the maximum number of fuel types that can be simulated by the RFSP [Ref. 6] code is ~35 depending on the size of auxiliary data used. For each clustering group (fuel types), cross-sections were generated by averaging compositions of fuels in the same clustering group. Then, the core calculations were performed by assigning the fuel types randomly to each bundle position. In this calculation, assumptions and analysis strategies were made as follows:

- The fuel burnup distribution is fixed. The effect of different fuel burnup distributions on the core performance should be assessed through refueling simulation.
- The distribution of heterogeneous fuels in the core is fixed too. The effect of different fuel type distributions on the core performance will be assessed through refueling simulation too.
- The parametric calculation on the number of fuel types will provide sensitivities of core performance parameters, when the number of fuel types is reduced from 30 to 1 by clustering similar fuel types.
- The neutronic property of each fuel type is generated using the average composition of fuels that belong to a clustering group. The uncertainty due to the use of average fuel composition should be assessed by an appropriate method.

Therefore, the sensitivity calculation on the number of clustering groups separates the effect of the number of fuel types from the integrated fuel composition heterogeneity effect by fixing the distributions of fuel burnup and fuel types in the core.

At first, the calculation was performed with a fixed ZCU water level of 0.5 which was used for the time-average core calculation. Therefore, the spatial and bulk control of ZCU are not working, which can show the effect of fuel type heterogeneity easily. In fact, the MCP, MBP, and CPPF do not change much once the number of fuel types is more than ten, indicating that the fuel composition heterogeneity was already greatly reduced. Though the sensitivity calculation has shown that the variations of core performance parameters are asymptotic when the number of clustering groups is more than ten, it was decided to use 30 fuel types in the heterogeneity analysis in order to consider the heterogeneity effect as much as possible within the capacity of core simulation code RFSP. The procedure to generate 30 fuel types is schematically shown in Fig. 2 and the distribution is shown in Fig. 3, respectively.

Secondly, the performance parameters were calculated by allowing the spatial and bulk control by ZCU to see how effectively the ZCU system compensates for the perturbations caused by the fuel composition heterogeneity. The MCP, MBP, and CPPF are summarized in Table I. It should be noted that the ZCUs are working to maintain the reference zone power distribution of the core. If there is a perturbation in zone power due to the fuel type heterogeneity, the ZCUs work to adjust the zone power, which could result in the MCP to either increase or decrease. As shown in Table I, there are no big changes in MCP, MBP, and CPPF, when the number of fuel types change, indicating that the fuel type heterogeneity is almost compensated by ZCUs.

### III.B. Uncertainty of Each Fuel Type

As mentioned in Sec. III.A, the heterogeneity effect was assessed assuming that there are heterogeneities among different fuel types but each fuel type has a uniform fuel composition. In fact, the fuel composition heterogeneity exists for each fuel type. For example, there are 34 different fuels for fuel type 13 as shown in Fig. 3. The effect of such a residual heterogeneity was assessed by selecting a fuel randomly from each clustering group instead of using group-average fuel property. Here again, the distribution of fuel types in the core is fixed, but the property of each fuel type is changed depending on the fuel randomly selected for the simulation. In order to cover most of the possible cases, a total of 100 simulations were performed. The difference of the channel power was calculated against the core simulation using group-average fuel properties as shown in Fig. 4. The differences were obtained with a 95% confidence level, and the core-average values are compared in Table II. It can be seen that the average differences of the channel power, bundle power and CPPF are 0.49, 0.57, and 0.46%, respectively.

### III.C. Refueling Simulation

The refueling simulation was performed with 30 fuel types and the results are compared with those of the refueling simulation with a single fuel type in Table III. The simulation has shown that the MCP and MBP of the heterogeneous core are almost the same as those of the single fuel type core. The CPPF was increased slightly (0.34%) in the heterogeneous core. If the uncertainty due to the group-average fuel composition (see Table II) is included, the uncertainties of the MCP, MBP and CPPF are expected to be 0.5, 0.7, and 0.8%, respectively. The result of this simulation indicates that the fuel composition heterogeneity was already reduced appreciably by fixing the isotopic contents of major fissile isotopes $^{235}$U and $^{239}$Pu and the composition variations of other isotopes have minor impacts on core performance parameters. It is also believed that the effects of fuel composition heterogeneity on core performance parameters are surely within the capability of reactor regulating system (RRS). The results of refueling simulations are shown in Figs. 5, 6, and 7 for MCP, MBP, and CPPF, respectively.

### III.D. Discussion

It is worth noting that the CANDU reactor accepts fresh fuels during normal operation to maintain the excess reactivity and reference power distribution. When a refueling channel is selected, the ZCU level is typically below the average level, which reserves a reactivity margin for the fresh fuel. Even if the reactivity of the fresh fuel is higher or lower than that of the nominal fuel (heterogeneity effect), the reactivity of the fresh fuel is surely higher than that of the irradiated fuel in the core. Therefore, the excess reactivity is provided to the core though the magnitude may change depending on the fuel type selected. However, such a deficit in the excess reactivity is compensated by the RRS represented by the ZCU. Even when the ZCU level increases too much, the extra reactivity can be easily accommodated by not refueling channels that belong to that specific ZCU. Therefore, the on-power refueling capability of a CANDU reactor provides an excellent flexibility to adjust the reactivity perturbations caused by the fuel composition heterogeneity.

## IV. SUMMARY AND CONCLUSION

The fuel composition heterogeneity effect on the core performance has been studied for three DUPIC fuel options. The composition heterogeneity was modelled by 30 fuel types which were generated by the AHC technique. The heterogeneity effect was assessed by performing core simulations with the single fuel type (average fuel composition) and 30 fuel types for each DUPIC fuel option. The comparisons have shown that the heterogeneity effects on MCP, MBP, and CPPF are less than 0.6, 1.5, and 0.8%, respectively. Therefore, the MCP and MBP are far below the license limits (7300 and 935 kW, respectively) even though the heterogeneity effects are considered. Such a small heterogeneity effect could be attributed to the composition adjustment method developed for the DUPIC fuel and the inherent zone power control mechanism associated with the on-power refueling capability of a CANDU reactor. In conclusion, the DUPIC fuel composition heterogeneity has only a minor effect on the core performance parameters under the condition that they are adjusted to have a uniform neutronic property.

## ACKNOWLEDGEMENT

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Table I

Effect of Number of Clustering Groups on Core Performance Parameters

(With Spatial and Bulk Control)

| Clustering Group | DUPIC Fuel Option | | |
|---|---|---|---|
| | MCP | MBP | CPPF |
| 1 | 6885 | 796 | 1.051 |
| 10 | 6843 | 805 | 1.055 |
| 15 | 6849 | 804 | 1.054 |
| 20 | 6844 | 805 | 1.056 |
| 25 | 6843 | 805 | 1.054 |
| 30 | 6849 | 805 | 1.054 |

Table II

Uncertainty of Core Performance Parameters due to Group-average Fuel Type

| Performance Parameter | Uncertainty (%) |
|---|---|
| Maximum channel power | 0.49 |
| Maximum bundle power | 0.57 |
| Channel power peaking factor | 0.46 |

Table III

Comparison of Core Performance Parameters

| Performance Parameter | DUPIC Fuel Model | | |
|---|---|---|---|
| | Single Fuel Type | 30 Fuel Types | Difference (%) |
| Maximum channel power (kW) | 6844 | 6843 | 0.01 |
| Maximum bundle power (kW) | 804 | 805 | 0.12 |
| Channel power peaking factor | 1.0625 | 1.0661 | 0.34 |

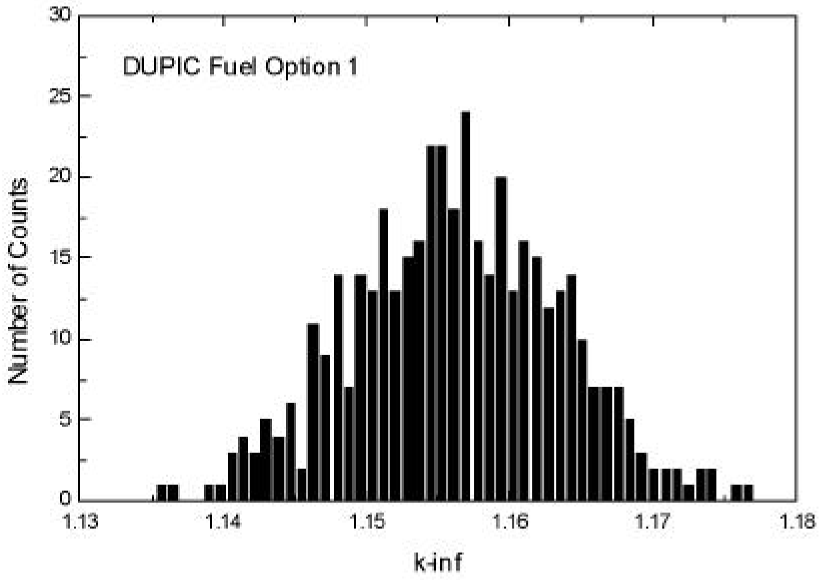


Fig. 1 $k_{\infty}$ Distribution of DUPIC Fuel

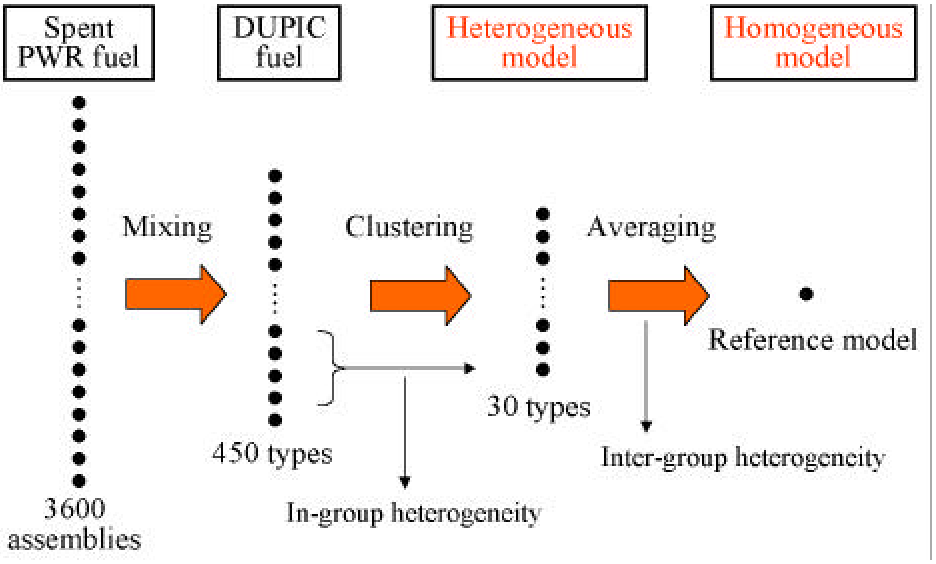


Fig. 2 Fuel Type Clustering Procedure

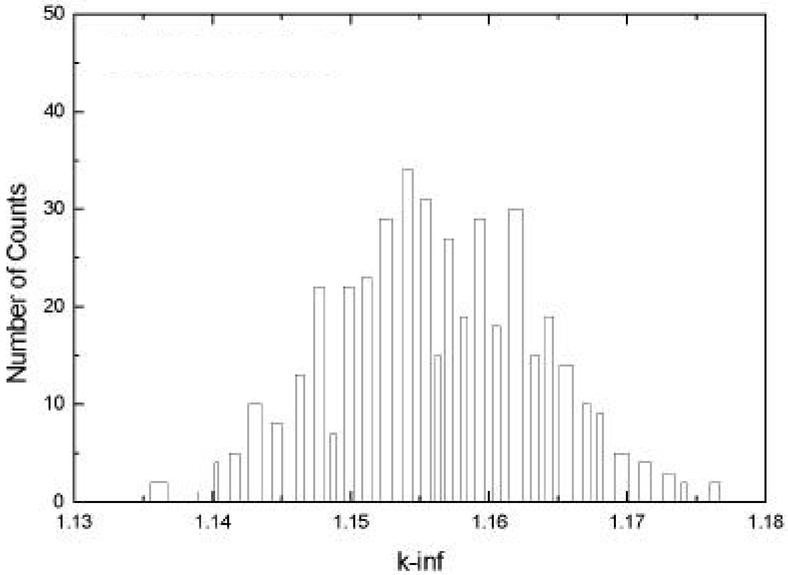
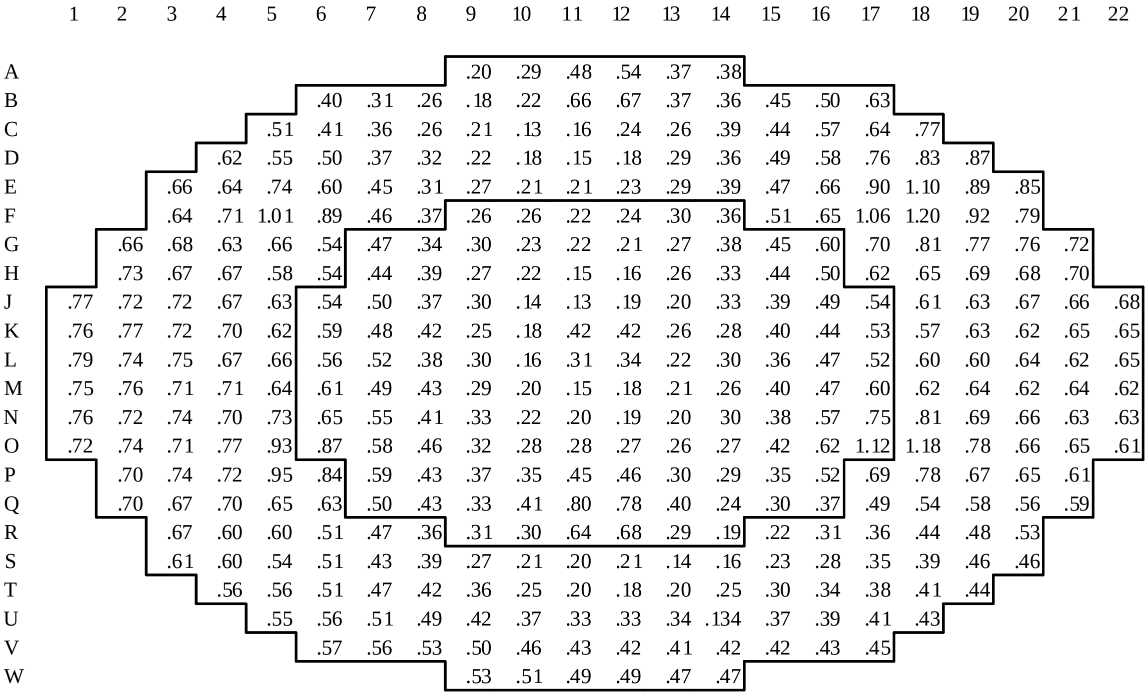


Fig. 3 Distribution $k_\infty$ for 30 Fuel Types



| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | | | | | | | | | .20 | .29 | .48 | .54 | .37 | .38 | | | | | | | | |
| B | | | | | | .40 | .31 | .26 | .18 | .22 | .66 | .67 | .37 | .36 | .45 | .50 | .63 | | | | | |
| C | | | | | .51 | .41 | .36 | .26 | .21 | .13 | .16 | .24 | .26 | .39 | .44 | .57 | .64 | .77 | | | | |
| D | | | | .62 | .55 | .50 | .37 | .32 | .22 | .18 | .15 | .18 | .29 | .36 | .49 | .58 | .76 | .83 | .87 | | | |
| E | | | .66 | .64 | .74 | .60 | .45 | .31 | .27 | .21 | .21 | .23 | .29 | .39 | .47 | .66 | .90 | 1.10 | .89 | .85 | | |
| F | | | .64 | .71 | 1.01 | .89 | .46 | .37 | .26 | .26 | .22 | .24 | .30 | .36 | .51 | .65 | 1.06 | 1.20 | .92 | .79 | | |
| G | | .66 | .68 | .63 | .66 | .54 | .47 | .34 | .30 | .23 | .22 | .21 | .27 | .38 | .45 | .60 | .70 | .81 | .77 | .76 | .72 | |
| H | | .73 | .67 | .67 | .58 | .54 | .44 | .39 | .27 | .22 | .15 | .16 | .26 | .33 | .44 | .50 | .62 | .65 | .69 | .68 | .70 | |
| J | .77 | .72 | .72 | .67 | .63 | .54 | .50 | .37 | .30 | .14 | .13 | .19 | .20 | .33 | .39 | .49 | .54 | .61 | .63 | .67 | .66 | .68 |
| K | .76 | .77 | .72 | .70 | .62 | .59 | .48 | .42 | .25 | .18 | .42 | .42 | .26 | .28 | .40 | .44 | .53 | .57 | .63 | .62 | .65 | .65 |
| L | .79 | .74 | .75 | .67 | .66 | .56 | .52 | .38 | .30 | .16 | .31 | .34 | .22 | .30 | .36 | .47 | .52 | .60 | .60 | .64 | .62 | .65 |
| M | .75 | .76 | .71 | .71 | .64 | .61 | .49 | .43 | .29 | .20 | .15 | .18 | .21 | .26 | .40 | .47 | .60 | .62 | .64 | .62 | .64 | .62 |
| N | .76 | .72 | .74 | .70 | .73 | .65 | .55 | .41 | .33 | .22 | .20 | .19 | .20 | 30 | .38 | .57 | .75 | .81 | .69 | .66 | .63 | .63 |
| O | .72 | .74 | .71 | .77 | .93 | .87 | .58 | .46 | .32 | .28 | .28 | .27 | .26 | .27 | .42 | .62 | 1.12 | 1.18 | .78 | .66 | .65 | .61 |
| P | | .70 | .74 | .72 | .95 | .84 | .59 | .43 | .37 | .35 | .45 | .46 | .30 | .29 | .35 | .52 | .69 | .78 | .67 | .65 | .61 | |
| Q | | .70 | .67 | .70 | .65 | .63 | .50 | .43 | .33 | .41 | .80 | .78 | .40 | .24 | .30 | .37 | .49 | .54 | .58 | .56 | .59 | |
| R | | | .67 | .60 | .60 | .51 | .47 | .36 | .31 | .30 | .64 | .68 | .29 | .19 | .22 | .31 | .36 | .44 | .48 | .53 | | |
| S | | | .61 | .60 | .54 | .51 | .43 | .39 | .27 | .21 | .20 | .21 | .14 | .16 | .23 | .28 | .35 | .39 | .46 | .46 | | |
| T | | | | .56 | .56 | .51 | .47 | .42 | .36 | .25 | .20 | .18 | .20 | .25 | .30 | .34 | .38 | .41 | .44 | | | |
| U | | | | | .55 | .56 | .51 | .49 | .42 | .37 | .33 | .33 | .34 | .134 | .37 | .39 | .41 | .43 | | | | |
| V | | | | | | .57 | .56 | .53 | .50 | .46 | .43 | .42 | .41 | .42 | .42 | .43 | .45 | | | | | |
| W | | | | | | | | | .53 | .51 | .49 | .49 | .47 | .47 | | | | | | | | |

Fig. 4 Channel Power Uncertainty due to Group-Average Fuel Property

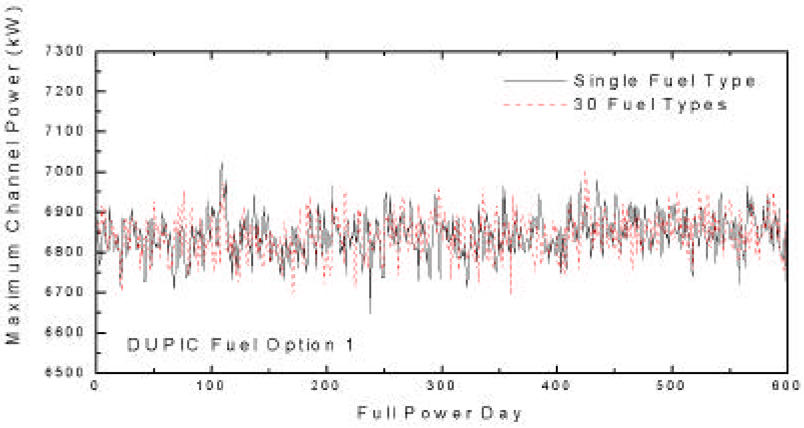


Fig. 5 Maximum Channel Power from Refueling Simulation

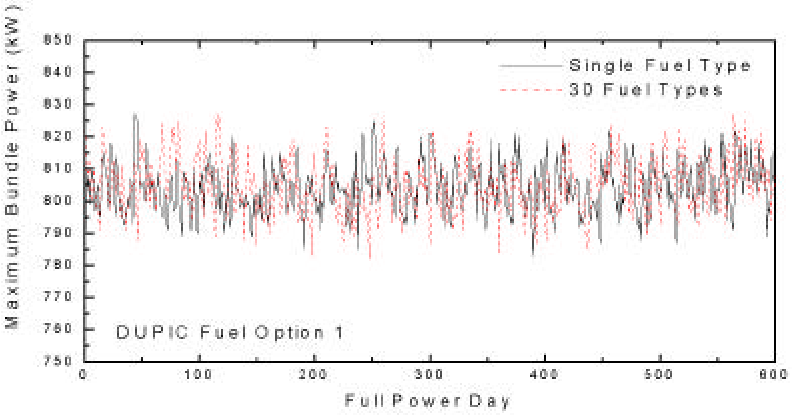


Fig. 6 Maximum Bundle Power from Refueling Simulation

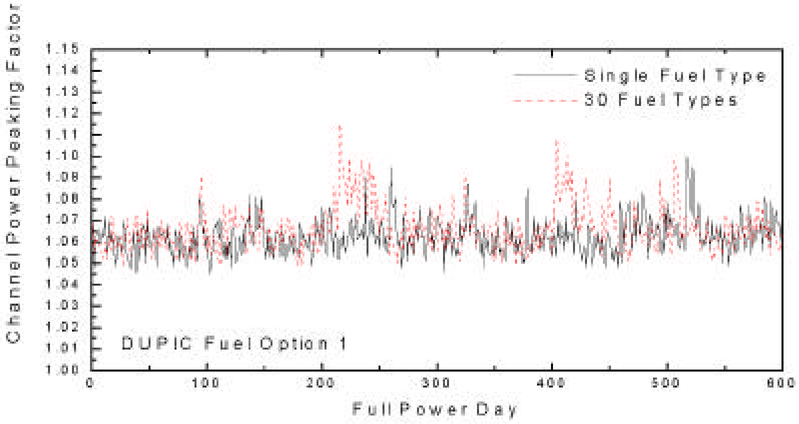


Fig. 7 Channel Power Peaking Factor from Refueling Simulation