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DUPIC Fuel Bundle Design Power Envelope Generation and Performance Analysis

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Abstract

This study describes the design power envelope generation procedure of the DUPIC fuel bundle. The intermediate results of the DUPIC fuel performance analysis based on the design power envelope have shown that the integrity of the DUPIC fuel is maintained under the high power and high burnup conditions even though the material property such as the thermal conductivity is a little lower when compared to the natural uranium fuel. At the moment however, it is required to perform more irradiation tests of the DUPIC fuel to accumulate a data base for the demonstration of the DUPIC fuel performance in the CANDU reactor.

1. Introduction

The DUPIC fuel cycle technology has been developed as an alternative to the conventional direct disposal or plutonium recycle options.[1] In order for the DUPIC fuel to be used in the CANDU reactor, the DUPIC fuel should withstand a continuous operation at a high power and the power level changes caused by a power ripple, reactivity shim and the refueling sequences.[2] In this study, the performance of the DUPIC fuel is assessed for the proposed fuel management strategy of the DUPIC fuel CANDU core, which shifts two fuel bundles per refueling operation. In order to assess the DUPIC fuel performance, a bundle power history (design power envelope) was generated from the refueling simulation. The performance of the DUPIC fuel was then assessed for the fuel failure probability, melting temperature and the internal pressure of the fuel element.

2. DUPIC Fuel Bundle Design Power Envelope

For the analysis of the DUPIC fuel performance in a CANDU reactor, the bundle power history was obtained by the RFSP [Ref. 3] code. At first the equilibrium core characteristics were calculated by the time-average model of the RFSP code, which provides the refueling rate, discharge burnup, power distribution and the fuel residence time. Then the refueling simulation was performed for 600 full power days (FPD), which is sufficient enough to refuel all the fuel channels at least once. The fueling scheme used for the DUPIC fuel core was a 2-bundle shift, while that for the standard natural uranium core is an 8-bundle shift.

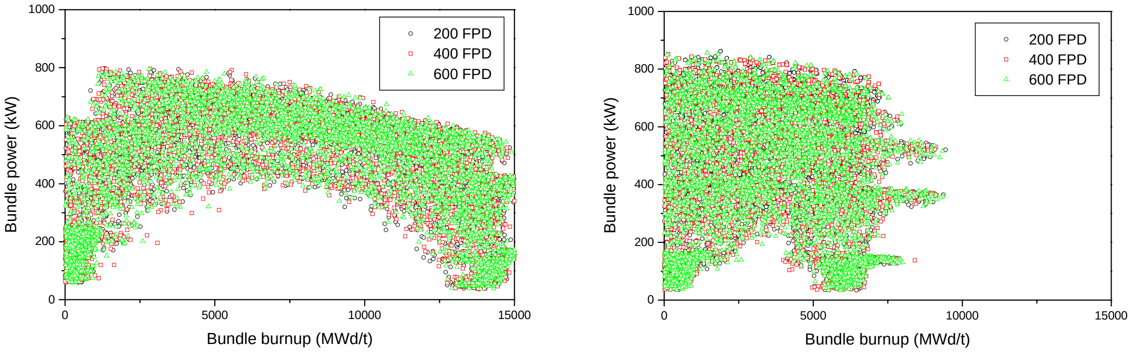
2.1 Reactor Physics Data

The results of the DUPIC fuel equilibrium core calculation are given in Table I and compared to those of the natural uranium core. The reactor core is divided into two radial regions of which the discharge burnup is adjusted to minimize the maximum channel power (MCP). It can be seen that the maximum bundle power (MBP) of the DUPIC fuel core is 764 kW (channel O-9) which is lower than that of the natural uranium core (827 kW at channel N-5) by 7.6%. It should be noted that both the MCP and MBP of the DUPIC fuel core are lower than those of the natural uranium core because the number of fuel bundles loaded per refueling operation is smaller for the DUPIC fuel core. The fuel dwell time is 93 FPDs for the DUPIC fuel, while it is 195 FPDs for the natural uranium. However because it takes six refueling operations for the DUPIC fuel to be discharged from a fuel channel, the DUPIC fuel residence time in the core is 560 FPDs.

Table I. Comparison of the time-average core characteristics

	DUPIC fuel core	Natural uranium core
Refueling scheme	2-bundle shift	8-bundle shift
Maximum channel power (kW)	6623	6732
Maximum bundle power (kW)	764	827
Refueling rate (channels/day)	4.07	1.93
Discharge burnup (MWd/t)	14825	7321
Form factor (average/maximum)	0.600	0.554
Fuel dwell time (FPD)	93.3	194.7

More comprehensive data for the bundle power is shown in Figs. 1(a) and 1(b) for the DUPIC fuel and natural uranium cores, respectively, based the 600-FPD refueling simulations. Both plots show snapshots of the bundle power distribution at 200, 400, and 600 FPD. The peak MBP during the 600-FPD simulation is 827 kW and 893 kW for the DUPIC fuel and natural uranium core, respectively. Compared to the time-average core, the MBP increases by 8.2% and 8.0% for the DUPIC fuel and natural uranium core, respectively, due to the refueling perturbation.



(a) DUPIC fuel core (b) Natural uranium core

Fig. 1. Comparison of the bundle power distribution

2.2 Bundle Radial Power Distribution and Linear Power

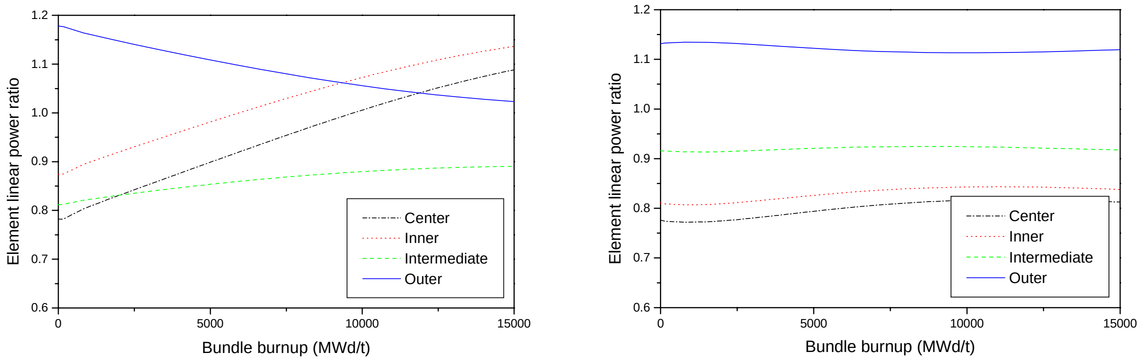
For the DUPIC fuel bundle, the element relative linear power steadily changes as the fuel burnup increases as shown in Fig. 2(a). Initially the outer elements have the highest relative linear power but the inner elements begin to produce more relative linear power when the bundle burnup is greater than ~9000 MWd/t. However, because the peak bundle power occurs at a relatively low burnup (~3000 MWd/t) as shown in Fig. 1, the outer fuel element will be the limiting fuel element as far as the element linear power is concerned. Table II estimates the element linear power of the nominal (time-average) and high power (refueling simulation) fuel bundle. For comparison, the element relative linear power and peak linear power are given in Fig. 2(b) and Table III, respectively, for the standard 37-element fuel bundle. It can be seen that the outer element dominates the peak linear power throughout the fuel burnup. As a result, the peak linear power is reduced by 10.9 kW/m for the DUPIC fuel compared to the standard natural uranium fuel, which corresponds to a 20% reduction.

Table II. Linear element power of the MBP DUPIC fuel

Ring	Number of elements	Nominal power		High power	
		Element linear power (kW/m)	Ring power (kW)	Element linear power (kW/m)	Ring power (kW)
Center	1	30.2	15	32.7	16
Inner	7	33.4	116	36.2	126
Intermediate	14	30.0	208	32.5	225
Outer	21	40.9	425	44.3	460
Total	43		764		827

Table III. Linear element power of the MBP natural uranium fuel

Ring	Number of elements	Nominal power		High power	
		Element linear power (kW/m)	Ring power (kW)	Element linear power (kW/m)	Ring power (kW)
Center	1	35.0	17	37.8	18
Inner	6	36.6	109	39.5	118
Intermediate	12	41.3	245	44.6	265
Outer	18	51.1	456	55.2	492
Total	37		827		893



(a) 43-element DUPIC fuel (b) 37-element natural uranium fuel

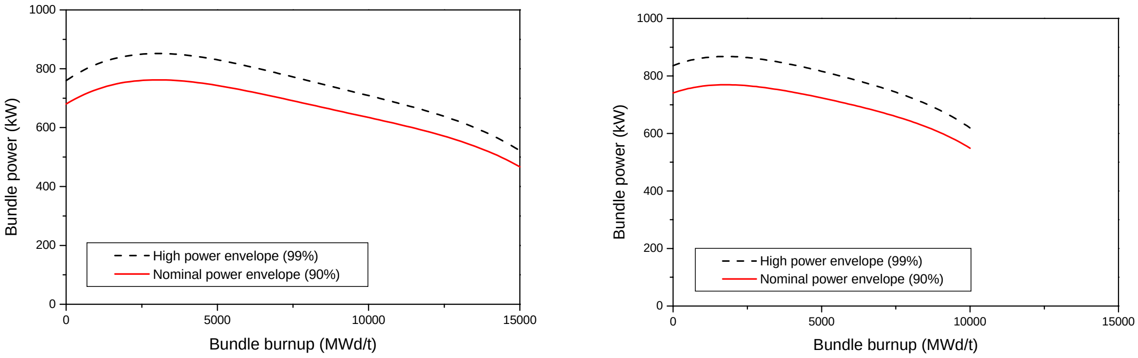
Fig. 2. Comparison of the element linear power ratio

2.3 Nominal Bundle Power and Reference High Power Envelope

The bundle power history is generated for the analysis of the DUPIC fuel performance in the CANDU reactor. If all the bundle powers of the DUPIC fuel core are plotted as a function of the fuel burnup, the design power curve is obtained from the MBP at each burnup step. Therefore the DUPIC fuel bundle design power envelope includes the representative power change of the fuel bundles for various fuel bunrups. The design power curve is obtained under the following conditions without considering the transient and measurement error:

- More than 99% of the fuel bundles in the reactor at a specified time have a power and burnup within the reference high power envelope.
- More than 90% of the fuel bundles in the reactor at a specified time have a power and burnup within the nominal design power envelope.

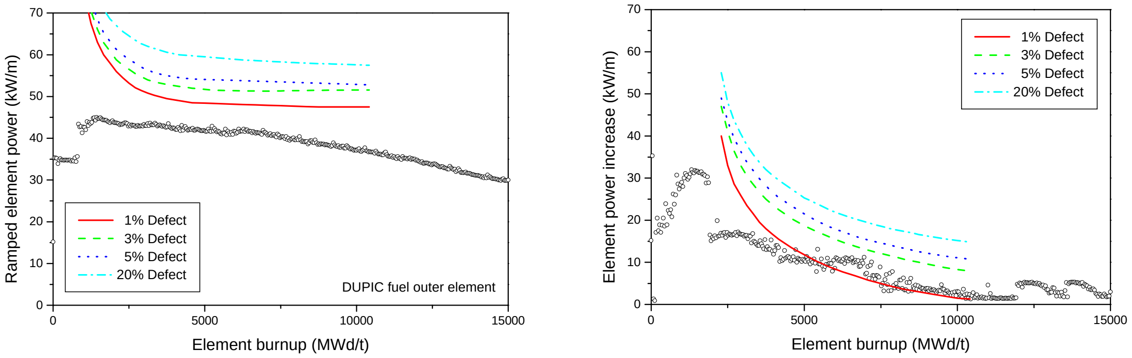
Figure 3 shows the bundle power envelopes of the DUPIC fuel and natural uranium fuel, respectively. For the DUPIC fuel bundle, the peak bundle power of the nominal design power envelope is 760 kW, which corresponds to a fuel burnup of ~3000 MWd/t. Considering the power increase due to the refueling, the peak bundle power of the high power envelope is 850 kW, which is far below the current license limit of the natural uranium fuel bundle (935 kW). Therefore the reference high power envelope of the DUPIC fuel bundle is higher than the nominal design power envelope by 12%.



(a) DUPIC fuel bundle (b) Natural uranium fuel bundle

Fig. 3. Comparison of the fuel bundle design power envelops

For the standard natural uranium fuel, it is recommended that the ramped bundle power and the bundle power fluctuation due to refueling should result in a defect probability of less than 3%. It is also known that the defect probability curves are conservative and the reactor operation within a 3% defect probability should result in no fuel defects caused by the power increase. For the DUPIC fuel bundle, the instantaneous peak element powers are compared to the defect probability curves in Fig. 4 for the ramped linear power and the linear power increase of the outer fuel element.



(a) Ramped linear power (b) Linear power ramp

Fig. 4. Linear power of the DUPIC fuel outer element

The comparison shows that the ramped linear power of the DUPIC fuel element is far below the defect probability curve, which is due to the flattened power distribution of the DUPIC fuel core. However the linear power increase exceeds the 3% defect probability curve when the element burnup is more than ~5000 MWd/t. This is directly due to the axial power distribution and the refueling scheme of the DUPIC fuel core which shifts two fuel bundles per refueling. Therefore it is expected that the proposed DUPIC fuel management doesn’t cause fuel defects under the assumption that the existing defect probability curves are applicable to the DUPIC fuel. In fact, the defect probability curve was derived based on the performance statistics of the natural uranium fuel.[4] However it should also be noted that the DUPIC fuel satisfies the natural uranium CANDU fuel specifications.

In the case of the natural uranium fuel, the element linear power exceeds the 1% defect probability curve but is within the 3% defect probability curve, while the linear power increase is well below the 1% defect probability curve. This is also due to the axial power shape and the 8-bundle shift refueling scheme of the natural uranium core. That is, the power shape of the natural uranium core is middle-peaked while that of the DUPIC fuel core is middle-humped in the axial direction of a fuel channel. Therefore one half of the once-irradiated fuels (4 bundles) is discharged from the channel and the rest of the fuel bundles are moved to the low power region. As a result, the linear power increase is high only for the low-burnup fuels in the natural uranium core.

3. DUPIC Fuel Performance

The fuel temperature and internal pressure of the DUPIC fuel were estimated by the ELESTRES [Ref. 5] code using the material properties measured for the DUPIC fuel. The estimated maximum fuel temperature was 2150 K from the reference high power envelope, while that of the natural uranium fuel was 1700 K. Therefore the estimated peak temperature of the DUPIC fuel is higher than that of the natural uranium fuel by 450 K, but is lower than the estimated melting temperature by 876 K. The internal pressure of the DUPIC fuel was estimated to be 8 MPa, which is 25% lower than the primary heat transport system pressure of 10.6 MPa, if the fuel element plenum volume is adjusted.

4. Summary and Conclusion

In order to assess the DUPIC fuel performance against the in-core fuel management strategy, the design power envelop was generated from the refueling simulation of the DUPIC fuel core. The fuel performance analysis was performed by the ELESTRES code for the major performance parameters. The results showed that the current DUPIC fuel design is acceptable for a full power operation in the CANDU-6 reactor under the 2-bundle shift refueling scheme. However the analysis also showed that minor design changes would be required to accommodate the high internal pressure and stress due to the fission products.

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