DUPIC FUEL PERFORMANCE FROM REACTOR PHYSICS VIEWPOINT

HANGBOK CHOI, BO W. RHEE, HYUNSOO PARK

Korea Atomic Energy Research Institute
P.O.Box 105, Yuseong, Taejon, Korea
choih@dupicfl.kaeri.re.kr

ABSTRACT

A preliminary study was performed for the evaluation of Stress Corrosion Cracking (SCC) parameters of nominal DUPIC fuel in CANDU reactor. For the reference 2-bundle shift refueling scheme, the predicted ramped power and power increase of the 43-element DUPIC fuel in the equilibrium core are below the SCC thresholds of CANDU natural uranium fuel. For 4-bundle shift refueling scheme, the envelope of element ramped power and power increase upon refueling are 8% and 44% higher than those of 2-bundle shift refueling scheme on the average, respectively, and both schemes are not expected to cause SCC failures.

I. INTRODUCTION

The cause of CANDU fuel defects is categorized into three mechanisms such as fretting by debris, Stress Corrosion Cracking (SCC), and manufacturing defects[1]. The most performance limiting fuel defect mechanism related to reactor operation is SCC[2,3] because it is a function of fuel burnup, ramped (final) power and power increase upon refueling. In general, the fresh fuel is very resistant to the SCC failure, but as the fuel is irradiated, the corrosive fission products accumulated in the fuel gap can cause failure of the sheath when combined with sheath stresses generated during a power ramp. This phenomenon is common to all Zircaloy sheath UO_2 fuels.

For the direct use of spent PWR fuel in CANDU (DUPIC), the higher fissile content of DUPIC fuel prohibits the use of typical 8-bundle shift refueling scheme, which enhances core characteristics different from natural uranium CANDU 6 reactor. The compatability of DUPIC fuel to CANDU reactor can be classified into several aspects such as mechanical compatability, controllability, safety, economics, etc. The geometry of 43-element CANFLEX bundle is suitable to current CANDU 6 fuel channel and refueling machine. The 2-bundle and 4-bundle shift refueling simulations[4] have shown that the channel and bundle powers satisfy the license limits of operation.

As a part of conceptual design of DUPIC fuel in normal operation, the fuel performance parameters were calculated for the possible refueling schemes of DUPIC core. Since the SCC threshold of DUPIC fuel is not available, the fuel performance parameters were compared to the SCC threshold of natural uranium fuel, referred to as 1982 SCC threshold curve by Manzer[5].

II. DUPIC FUEL BUNDLE DESIGN

Fuel Composition

The nominal DUPIC fuel[6] is made of spent PWR fuel which has an initial enrichment of 3.5 w/o and a discharge burnup of 35000 MWD/T. It was assumed that the spent PWR fuel is cooled for ten years before decladding and is refabricated by an oxidation-reduction process (OREOX)[7]. The fuel density is currently assumed to be 10.4 g/cm^3. By the nature of OREOX process, the volatile and semi-volatile fission products are removed and all the fuel materials and solid fission products are directly reused as DUPIC fuel. The composition of major fuel material is given in Table 1.

Fuel Bundle

The DUPIC fuel bundle design utilizes CANFLEX geometry which has 43 fuel elements to enhance thermal margin and reduce the peak linear element rating. The fuel bundle contains a poisoned element at the center in order to reduce the coolant void reactivity by increasing parastic capture of neutrons upon coolant voiding. The poison material used in the center element is a grey absorber (natural dysprosium) so that the void reactivity is suppressed throughout the irradiation time.

The poison material in the center pin increases the relative linear power of the outer element more than that of natural uranium fuel bundle at the early stage. As the fuel is irradiated, the location of peak relative linear power is shifted to the second ring as shown in Table 2.

III. DUPIC FUEL PERFORMANCE

Power Envelope

The refueling simulation was performed for the nominal DUPIC core by RFSP[8] using 2-bundle and 4-bundle shift refueling schemes. The simulation continues until the core reaches the equilibrium state where most channels have been refueled at least once. The ramped bundle power and power increase were calculated at every full power day (FPD). The maximum and minimum powers of fuel element were obtained for every burnup interval of 1 MWh/kg and the envelopes of ramped element power and power increase are plotted in Figures 1 and 2, respectively.

Unlike natural uranium fuel, the high power envelope decreases linearly as fuel burnup because there is no plutonium buildup for mid-burnup DUPIC fuels. But the power increase upon refueling is relatively large for low burnup fuels because of channel-front-peaked axial power shape and high fissile content. For 4-bundle shift refueling scheme, the maximum and average changes of ramped power are 51% and 8%, respectively, compared to 2-bundle shift. The ramped power is mostly high for the fuel of which the element burnup is less than approximately 150 MWh/kg because fuel bundles are located at high flux region during that period.

The envelope of power increase is higher for 4-bundle shift refueling scheme by 44% on the average compared to 2-bundle shift. For 4-bundle shift, the bundle displacement and residence time are twice those of 2-bundle shift and the magnitude of power increase is relatively *high* until the fuel bundle is located in the middle, i.e., the high bundle power region of a channel.

Power History

The ramped power is strongly dependent on the axial power shape of a channel. For example, the element ramped power of 2 bundles loaded in channel M4, which has the peak bundle power in the time-average core, are plotted in Figure 3 as a function of element irradiation until those bundles are discharged. As shown in Figure 3, the ramped power changes abruptly when the channel M4 was refueled. Between 2 refueling operations, the ramped power is slowly decreasing because of fissile burnout with a small fluctuations due to zone controller level change.

The power increase upon refueling can be easily obtained from Figure 3 and is shown in Figure 4 for 2-bundle shift refueling scheme. The fuel element gets the highest power increase when the fuel bundle is shifted at the channel front region where the channel power is the highest. For CANDU reactor, all the fuel bundles experience the linear power increase whenever the channel is refueled. In order to keep enough margin to SCC threshold, the refueling operation should be done in an appropriate time interval such that a fuel of high burnup is not positioned at the high flux region. Also the refueling simulation should be optimized such that the reference (time-average) power distribution is maintained.

IV. SCC THRESHOLD OF DUPIC FUEL

The SCC threshold of DUPIC fuel may be different from the empirically derived ones of natural uranium CANDU fuel. If the density of DUPIC fuel is determined lower than the normal range specified for natural uranium fuel, the densification effect will increase accordingly. As the fuel is irradiated, the net effect of densification and swelling on the sheath stress and strain could be less than that of natural uranium fuel for the same pellet design. But the internal design of fuel element may require small modifications to accommodate the high burnup of DUPIC fuel which is twice that of natural uranium fuel.

In general, it is expected that there are three concerns for the performance of low density and high burnup DUPIC fuel:

- the fuel element dimensional stability due to densification effect,
- the SCC threshold change due to fuel element density and dimension, and
- the SCC threshold of DUPIC fuel for high burnup region.

V. CONCLUSION

The flatter power distribution of DUPIC core may provide sufficient margin to prevent SCC failures and small changes to the SCC thresholds of DUPIC fuel. If the margin to SCC failure is found to be not enough, 2-bundle shift refueling scheme may be required as compared to 4-

bundle shift scheme in order to reduce the power ramps caused by refueling operation.

It is expected that the envelopes of fuel performance parameter could be reduced more if the refueling simulation is optimized such that power ripple is minimized. At the same time, it is necessary to develope a theoretical basis for the SCC threshold of DUPIC fuel and to verify by experiments.

REFERENCES

1. M. Gacesa, et al., "Canadian Fuel Development Program", Third International Conference on CANDU Fuel, Chalk River, Canada (1992).
2. M.R. Floyd, et al., "Behaviour of Bruce NGS-A Fuel Irradiated to a Burnup of ~500 MWh/kgU", Third International Conference on CANDU Fuel, Chalk River, Canada (1992).
3. A.M. Manzer, R. Sejnoha and M. Tayal, "Heavy Fuel for CANDU-6: Design Considerations", Third International Conference on CANDU Fuel, Chalk River, Canada (1992).
4. H.B. Choi, B.W. Rhee, and H.S. Park, "Comparison of Refueling Schemes for DUPIC Core", 4th International Conference on CANDU Fuel, Pembroke, Canada (1995).
5. A.M. Manzer and M.C. Chow, "Fuel Management Flexibility with Single-Ended Refuelling in CANDU 3", 11th Annual Conference of Canadian Nuclear Society, Toronto, Ontario, Canada (1990).
6. H.B. Choi, B.W. Rhee, and H.S. Park, "Parametric Analysis of the DUPIC Fuel Cycle", Canadian Nuclear Society 1994 Nuclear Simulation Symposium, Pembroke, Canada (1994).
7. M.S. Yang, et al., "Conceptual Study on the DUPIC Fuel Manufacturing Technology", Proc. International Conference and Technology Exhibition on Future Nuclear System: Emerging Fuel Cycles and Waste Disposal Options, GLOBAL'93, Seattle (1993).
8. B. Rouben and D.A. Jenkins, "Calculation of 3-D Flux Distributions in CANDU Reactors Using Lattice Properties Which Include the History of the Lattice", 12th Annual Canadian Nuclear Society Conference, Saskatoon, Canada (1991).

TABLE 1. COMPOSITION OF REFERENCE DUPIC FUEL (KG/BUNDLE)

Isotope	Fresh Fuel 0.0 MWD/T	Equilibrium Fuel 7452.9 MWD/T	Discharged Fuel 15039.9 MWD/T
U235	0.16291	0.10021	0.05171
U236	0.08088	0.08931	0.09498
U238	17.20170	17.12662	17.03359
Pu238	0.00195	0.00249	0.00292
Pu239	0.09766	0.07540	0.06141
Pu240	0.04059	0.05136	0.05681
Pu241	0.01479	0.01476	0.01502
Pu242	0.00934	0.01282	0.01779
Am241	0.00944	0.00547	0.00277
$Am242^m$	0.00001	0.00005	0.00003
Am243	0.00193	0.00282	0.00404

TABLE 2. RELATIVE ELEMENT BURNUP AND LINEAR POWER OF DUPIC FUEL

Bundle Burnup (MWD/T)	Relative Element Burnup				Relative Element Linear Power			
	Ring 1	Ring 2	Ring 3	Ring 4	Ring 1	Ring 2	Ring 3	Ring 4
0.000	1.000	1.000	1.000	1.000	0.437	0.853	0.806	1.205
162.749	0.355	0.655	0.863	1.292	0.439	0.854	0.807	1.204
1133.772	0.361	0.662	0.869	1.285	0.464	0.884	0.821	1.183
2422.986	0.372	0.674	0.876	1.273	0.497	0.915	0.834	1.163
4029.984	0.388	0.689	0.885	1.260	0.541	0.952	0.849	1.139
5636.940	0.405	0.703	0.893	1.247	0.587	0.988	0.861	1.116
7243.989	0.423	0.717	0.900	1.234	0.637	1.021	0.871	1.096
8851.334	0.442	0.730	0.907	1.223	0.688	1.052	0.880	1.078
10459.177	0.462	0.743	0.913	1.212	0.740	1.080	0.886	1.062
12067.153	0.482	0.755	0.918	1.201	0.792	1.104	0.890	1.048
13676.419	0.502	0.767	0.922	1.192	0.842	1.125	0.893	1.037
15286.700	0.522	0.777	0.926	1.183	0.888	1.141	0.894	1.029
16898.512	0.542	0.787	0.929	1.175	0.928	1.153	0.894	1.023
18511.926	0.561	0.796	0.931	1.168	0.961	1.160	0.893	1.020
20127.057	0.579	0.804	0.933	1.162	0.986	1.164	0.891	1.018

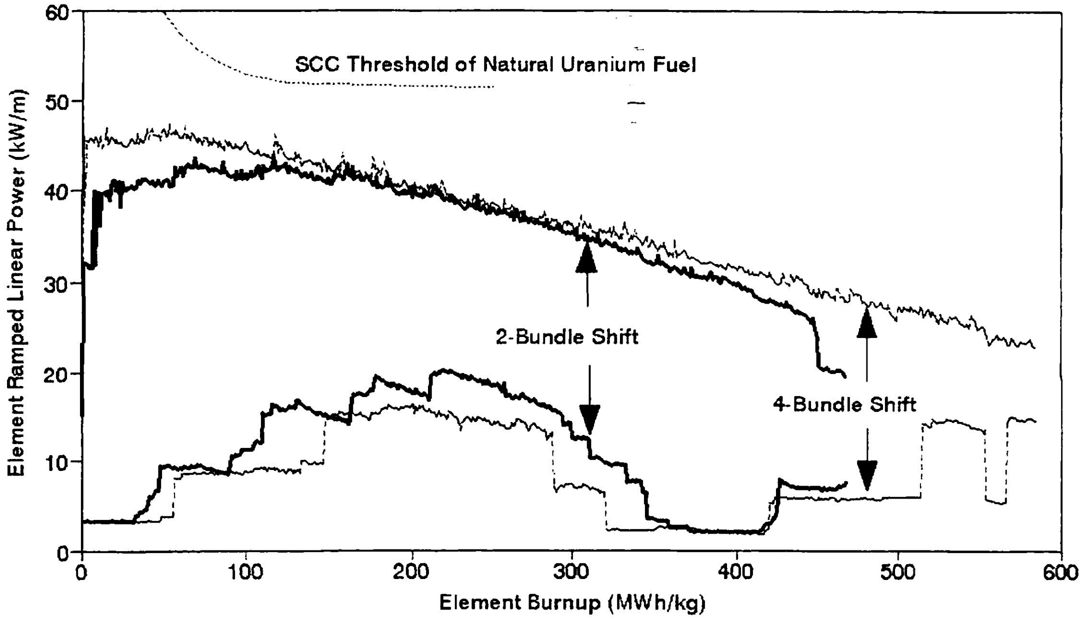

FIGURE 1. ELEMENT RAMPED POWER (KW/M) FOR DUPIC FUEL

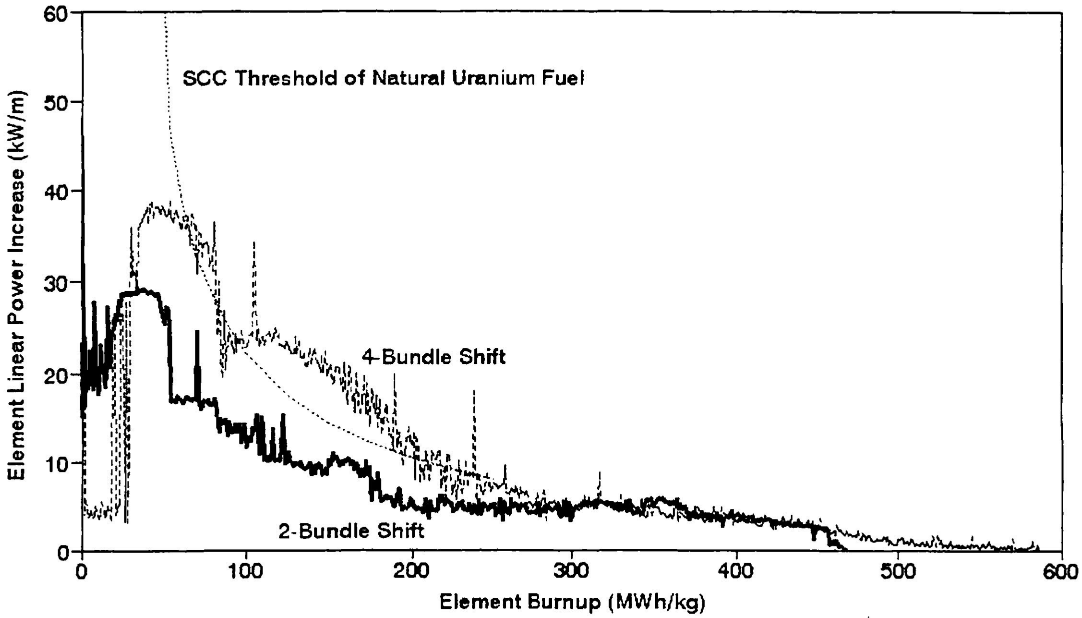

FIGURE 2. ELEMENT POWER INCREASE (KW/M) FOR DUPIC FUEL

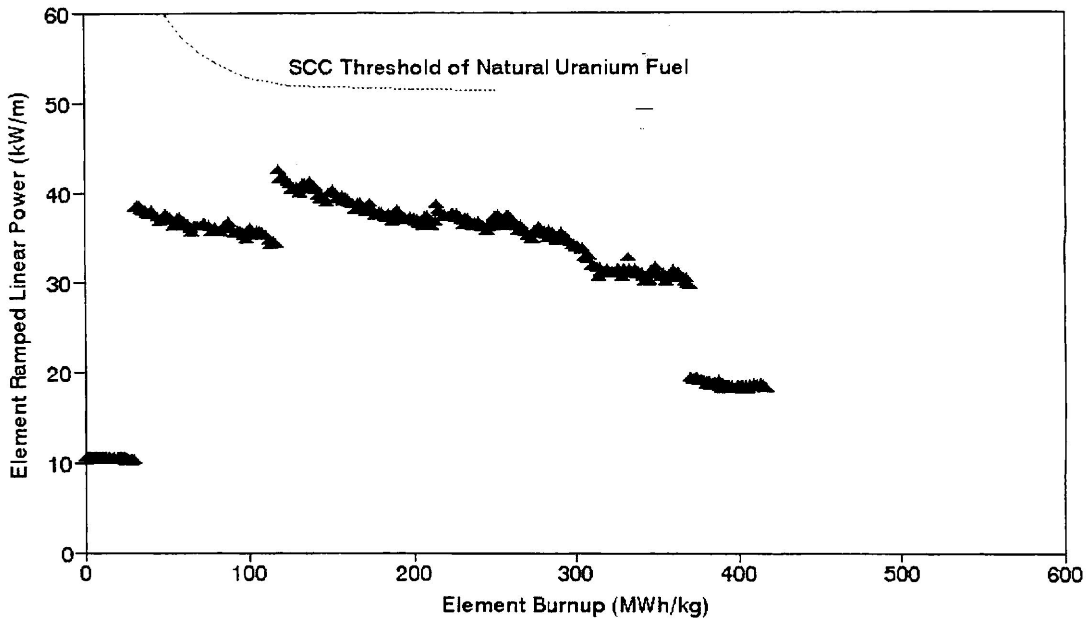

FIGURE 3. ELEMENT RAMPED POWER (KW/M) OF BUNDLES IN CHANNEL M4 (2-BUNDLE SHIFT REFUELING SCHEME)

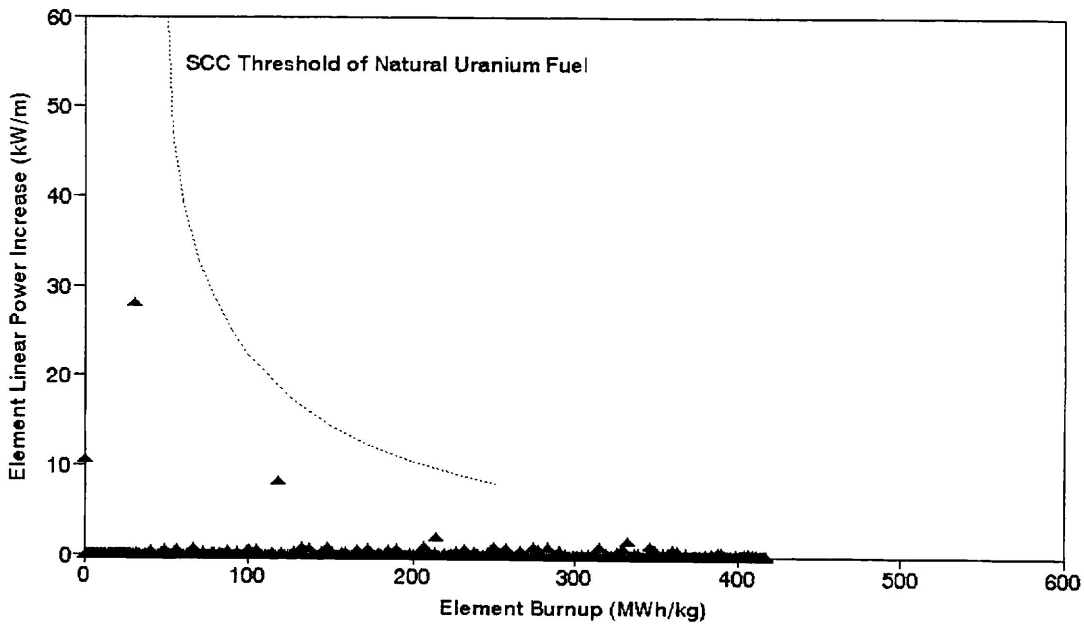

FIGURE 4. ELEMENT POWER INCREASE (KW/M) FOR BUNDLES IN CHANNEL M4 (2-BUNDLE SHIFT REFUELING SCHEME)