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Neutronic Evaluation of an OPR-1000 Core with Accident Tolerant Fuel and Cladding

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1. Introduction

The recent events at the Fukushima Daiichi nuclear power plant in Japan highlight the need to consider fuel and/or cladding with enhanced accident tolerance. One advanced fuel concept is the fully ceramic micro-encapsulated (FCM) fuel [1]. FCM fuel is based on a proven technology that has been utilized operationally in HTGRs. FCM fuel pin consists of fuel pellets where tri-isotropic (TRISO) particles are highly packed in a dense silicon carbide (SiC) matrix.

The objective of this study is to assess the feasibility of replacing conventional UO_2 fuel of existing LWRs with accident-tolerant FCM fuel. A Korean OPR-1000 was selected as the reference core for evaluating the operational performance of FCM fuels in LWR. Since the fissile density within a FCM fuel pin is significantly reduced when contrasted with a conventional UO_2 pin, uranium nitride (UN) with enhanced uranium density is encapsulated in a large diameter fuel kernel of 800 µm. Zirconium (Zr) alloy with a thin SiC coating is used as the cladding material to improve oxidation resistance.

2. Methods and Results

2.1 Design and Analysis Tools

The DeCART2D/MASTER two-step procedure is used as a reactor physics analysis tool for this study. The transport lattice calculations are performed by the DeCART2D [2] code to generate few-group cross sections, which are then tabularized as a function of burnups and temperatures by using the PROLOG code. Effective reflector cross sections are obtained by a 2-dimensional whole-core calculation using DeCART2D. A core physics analysis is carried out by the MASTER [3] code with these tabularized cross sections.

2.2 Fuel Assembly Design

Table I shows the design parameters of the FCM fuel assembly determined by results from the previous work [4]. Fuel rod diameter was decided by thermal-hydraulic analysis. It is assumed that a packing fraction of TRISO particles in a SiC matrix is 45%. Because the uranium loading is reduced up to 31% compared to a reference, the enrichment of the fuel kernel must be increased.

To identify the neutronic characteristics of the FCM fuel assembly design, the DeCART2D calculations were performed with the HELIOS [5] 47-group neutron and 18-group gamma libraries. Fig. 1 shows the k-infinity versus the moderator-to-fuel ratio. Since the FCM fuel design is under-moderated, the moderator temperature coefficient (MTC) could be negative. Fig. 2 shows the FCM assembly k-infinity as a function of burnup. The FCM fuel requires the ^{235}U enrichment up to 14.0 w/o to satisfy the required cycle length. As burnable absorber for the control of higher excess reactivity, erbia (Er_2O_3) was used in particle form called bi-isotropic (BISO) in all fuel rods. Thus, five different assembly types divided into ^{235}U enrichments and erbia contents were selected for core design.

Table I: Design Parameters of the FCM Fuel Assembly

Item	Reference (PLUS7)	FCM
Fuel Material	UO_2	UN
Pellet Radius (cm)	0.4095	0.4340
Clad Material	Zr-alloy	Zr-alloy+SiC
Clad Outer Radius (cm)	0.4750	0.5000
Clad Thickness (cm)	0.0570	0.0570+5µm
Uranium Loading Ratio (%)	100	31

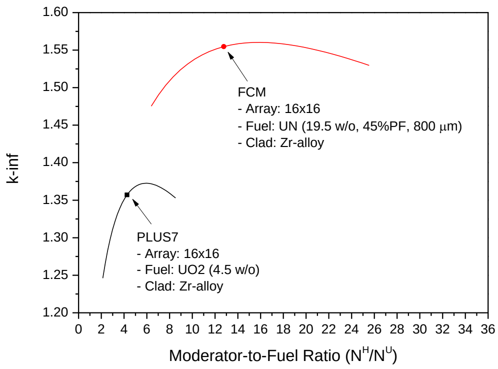

Fig. 1. Comparison of k-infinity vs. moderator-to-fuel ratio.

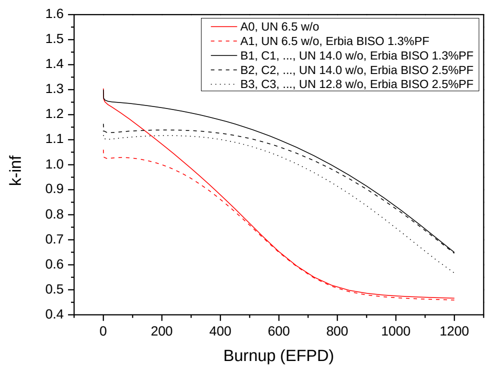

Fig. 2. FCM assembly k-infinity as a function of burnup.

2.3 Equilibrium Core Design

FCM core design features a two-batch and a low-leakage loading pattern. The design targets considered in the present study include:

1) an 18-month cycle with a capacity factor of 89% and availability factor of 92%, ≥ 450 EFPD,

2) power peaking during the cycle satisfies Fq ≤ 2.3, Fr ≤ 1.65, and Fz ≤ 1.4,

3) axial offset (AO) ≤ ±10%,

4) MTC < 0 at hot full power (HFP), and < +9 pcm/°C at hot zero power (HZP).

Five successive cycles from the first cycle are investigated by employing a fixed loading pattern to explore the desired power and burnup distributions for the equilibrium core. The cycle-by-cycle MASTER core calculations were performed with the tabularized cross section library for the FCM assemblies shown in Fig. 2.

Fig. 3 shows the core loading pattern in octant core configuration and end-of-cycle (EOC) power/burnup distribution for cycle 5 chosen as the equilibrium core. Core consists of 92 fresh fuel assemblies (F1, F2 and F3), and 85 once-burned fuel assemblies (E1, E2 and E3). Since discharge burnup of the FCM fuel assembly reaches up to 124 MWD/kgU due to a lower uranium loading, the fast fluence (> 0.18 MeV) of the FCM fuel assembly may exceed tentative limit of 1.5x10^{22} n/cm^2 determined by fuel performance analysis.

E2 0.777 0.805 122.938	F2 1.210 1.290 71.901	E2 0.806 0.840 121.265	F2 1.232 1.322 73.224	E3 0.751 0.789 118.099	F2 1.301 1.393 73.093	E1 1.015 1.123 102.560	F1 0.944 1.307 45.398
	E2 0.784 0.819 122.508	F2 1.223 1.307 72.729	E2 0.878 0.978 115.396	F2 1.260 1.368 73.218	E2 0.886 0.954 119.871	F2 1.281 1.430 66.402	E1 0.640 0.904 95.993
		E3 0.740 0.773 117.637	F2 1.242 1.350 72.847	E2 0.832 0.873 122.874	F2 **1.329** 1.406 73.754	F1 1.236 1.412 65.075	E2 0.483 0.772 95.908
			E2 0.808 0.845 **123.826**	F3 1.243 1.320 70.696	E1 0.969 1.112 108.629	F1 1.041 1.415 52.229	
				E1 1.072 1.221 102.461	F2 1.194 **1.443** 58.830	E2 0.508 0.807 95.234	
				Assembly Type - Assembly Power - Peak Pin Power - Assembly Burnup (MWD/kgU) -	F1 0.884 1.373 40.231		

Fig. 3. EOC power/burnup distribution for cycle 5.

Table II summarizes the typical core performance and safety parameters for cycle 5 of the FCM core and for cycle 6 of Hanbit Unit 3 as a reference core. The FCM core satisfies the cycle length requirement of 450 EFPD, the cycle maximum critical boron concentration (CBC) is similar to those of the reference. The change of axial offset (AO) is relatively smaller and the peaking factors are slightly larger in comparison to the reference. The MTC is less negative and the shutdown margin (SDM) is slightly larger when compared to the reference. From these results, it is concluded that the FCM core has a comparable performance in typical OPR-1000 cores.

Table II: Comparison of Typical Core Parameters

Item	Reference	FCM
Cycle Length (EFPD)	470	467
Cycle Max. CBC (ppm)	1,475	1,477
AO Range (%)	-2.8/+6.3	-1.5/-0.3
Cycle Max. Peaking Factors		
Fq	1.813	1.923
Fr	1.494	1.483
Fz	1.212	1.294
Cycle Max. MTC (pcm/°C)		
HFP	-17.44	-12.83
HZP	+2.63	+4.32
Cycle Min. SDM (pcm)	7,429	8,917

3. Conclusions

Neutronic feasibility study to use accident tolerant fuel and cladding in OPR-1000 core has been performed. The results show that the OPR-1000 core design fully loaded with FCM fuel is feasible and promising in neutronic aspects. However, since low uranium loading in the FCM fuel results in many challenging issues such as large reactivity gradient, high discharge burnup and fast fluence, additional study is needed.

ACKNOWLEDGEMENTS

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