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A Physics Characteristics Evaluation of a Fuel Assembly Loaded with LEU FCM Fuel in a LWR

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1. Introduction

Reducing the temperature of a fuel rod is a key in enhancing the safety of a nuclear reactor as well as increasing the reactor performance. When the operating temperature of the fuel is low, there is little chance of a fuel failure, and low fission product releases are few. The designer can increase the reactor power using the margin provided by the low fuel temperature. FCM (Fully Ceramic Micro-encapsulated) fuel is the recently developed fuel form [1]. A TRISO coated particle is encapsulated in a dense SiC matrix which is sintered with nano particles of SiC. TRISO has been used in various HTGR and its manufacturing technology is well established [2]. In an FCM, dense SiC matrix is serving as another protective barrier for a radioactive element release over pre-existing three-coated layers of TRISO. In a previous study, the application of an FCM with a trans-uranics (TRU) kernel in a light water reactor was conducted [3].

To use FCM fuel with LEU in an existing LWR, it is essential to study the neutronics compatibility with the existing LWR fuel assembly. A similar power generation rate with a solid UO_2 fuel assembly can be checked by the behavior of neutron multiplication factor over the fuel assembly lifetime.

In this paper, the results of assembly level calculations are presented to assess the preliminary feasibility of using a UN FCM fuel assembly in an OPR-1000, which is a typical PWR in Korea.

2. Analysis Results

2.1 Replacing Fuel Pellet with FCM Compact

The simple idea of using FCM fuel in a LWR is to use an FCM compact that has the same diameter as a solid pellet in the same cladding tube. A previous study on using TRU FCM fuel studied the possibility through fuel assembly calculation, full core calculation, and safety analysis on an OPR-1000 reactor. The results of the assessment were very positive. Inspired by a previous study, it started a feasibility study on using LEU FCM fuel on a LWR.

A typical TRU kernel has a high fraction of fissile material. However, an LEU kernel has a commercial limitation in enrichment below 20 w/o. It consider a proper LEU kernel to have U_{235} enrichment between 10 - 15 w/o. Lower enrichment is suitable in the manufacturing and non-proliferation aspects. From the results of the multiplication factor, higher enriched FCM fuel can achieve a higher burnup. A smaller diameter kernel gives a higher neutron multiplication factor. This is due to better moderation by graphite material surrounding the kernel and SiC matrix. High discharge burnup is better in respect of reducing nuclear waste at a final disposal. Due to the lower fuel inventory in FCM fuel, FCM fuel can achieve a 6- to 7- times higher discharge burnup compared with solid UO_2 fuel. The TRISO particle has proved its performance at very high burnup in HTGRs, where typical discharge burnup in an LEU fuel is 120 GWd/MTU.

The depletion rate is a key parameter for compatibility with solid fuel. To decrease the depletion rate, it is essential to increase self shielding by a higher fuel density, larger kernel diameter, and higher packing fraction. Figure 1 displays the results of the depletion calculation for 15 w/o enrichment, a 1,000 μm kernel diameter. The depletion rate of FCM fuel compared with solid fuel is too fast. The UCO kernel shows slightly better results than a UO_2 kernel. The depletion rate of a UN kernel best approaches that of solid fuel.

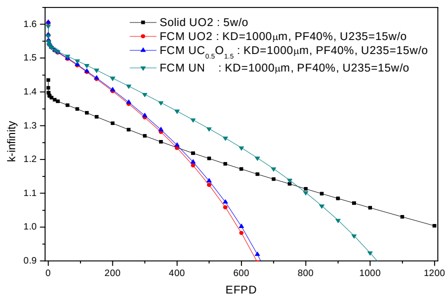

Fig. 1. Comparison of depletion rates.

2.2 Adoption of a Larger Diameter FCM Compact

A larger diameter compact has an advantage in self shielding as well as in achieving higher packing fraction by a lesser wall effect. It is selected a 12x12 configuration to replace a 16x16 fuel assembly. As shown in Figure 2, the selected configuration can maintain the same control rod position in the case of an OPR-1000. The diameter of fuel rod is determined so that the enthalpy rise in the channel is same as that of the existing fuel assembly.

With the same assembly pitch of 20.58 cm, the rod pitch of a 12x12 fuel assembly is 1.715 cm, while that of a 16x16 fuel assembly is 1.2863 cm. The fuel rod diameter is determined to be 1.594 cm from 0.950 cm.

After considering the clad to compact gap, which will be determined by the fuel rod assembly process, the pellet diameter increases to 1.451 cm from 0.819 cm. This is about a 1.77-times increment in pellet diameter in comparison to the 16x16 configuration.

The UN fuel kernel is introduced as the reference kernel for the FCM fuel in this study. The assembly calculation is done by McCARD [4] and DeCART [5] codes. The fuel temperature, coolant temperature, and coolant density are taken as 900 K, 600 K, and 0.7 g/cc, respectively.

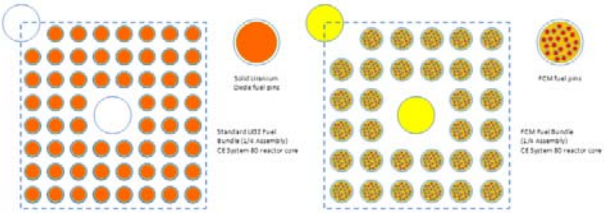

Fig. 2. 1/4 FA for OPR-1000: Left 16X16, Right 12X12.

Figure 3 shows the results of neutron multiplication factors of a UN FCM fuel assembly in comparison with a 4 w/o 16x16 solid fuel assembly. It can be seen that as the initial heavy metal mass increases, or enrichment decreases, the reactivity at a lower burnup is decreasing and that at a higher burnup is increasing. This is due to a conversion of fertile (U-238) into fissile (Pu-239) during depletion and the self-shielding effect.

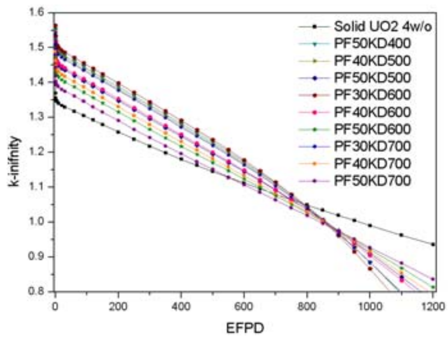

Fig. 3. K-infinity of the UN FCM fuel assembly.

2.3 Burnable Poison Effect

The use of a solid burnable poison (BP) is necessary to suppress the initial excess reactivity of FCM fuel. Two candidate burnable poison elements are considered in this study. In a previous study on the TRU FCM fuel, it is found that the natural gadolinia mixed in an FCM compact matrix burns too fast. It suggests the use of a BISO gadolinia kernel, which will be compactized with the TRISO fuel particle. In addition, less absorbing erbium is considered in this study. Natural erbia has a long-term effect with relatively a small residual poison at the end of the assembly life. The BP of erbia is mixed homogeneously in a SiC matrix of an FCM compact. Figure 4 compares the effect of burnable poisons for a UN FCM assembly. Gadolinia poisons burn too fast, whether homogeneously mixed in a matrix or in BISO form. The 1% volume fraction of erbia in a matrix shows a reasonable depletion shape. This is expected due to a low absorption cross section of erbia.

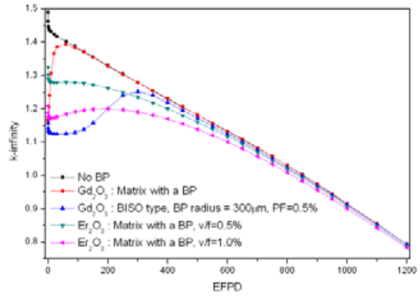

Fig. 4. Effect of the burnable poisons: UN FCM fuel.

2.4 Reactivity Coefficients

Negative feedback is important in the operation of a nuclear reactor. As the fissile material decreases, the system becomes over-moderated in a FCM fueled fuel assembly. For 4 w/o enriched solid UO_2 fuel, the thermal neutron fraction does not vary much during the depletion. However, in FCM fuel, the thermal neutron fraction increases significantly during depletion.

Figure 5 shows the MTC at 500 ppm for 700 μm kernels. For UN FCM fuels, the MTC remains negative over the lifetime. However, UCO and UO_2 FCM fuels have a positive MTC near the end of their life. This issue may be resolved when an actual core loading pattern and corresponding critical boron letdown curve over the core cycles are determined. They indicate that the burnable poison in the FCM fuel compact is very important in the MTC.

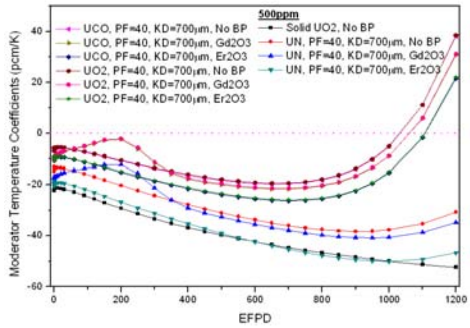

Fig. 5. MTC for 700 μm kernel at 500 ppm soluble boron.

Fuel temperature coefficients and soluble boron worth are also analyzed for UO_2, UCO, and UN FCM fuels. It indicates that the FTC remains negative for the burnup period and the soluble boron worth is also negative.

3. Conclusions

The fuel assembly with FCM fuels has been analyzed in the paper. It is possible to replace the 16x16 solid fuel assemblies of the OPR-1000 with 12x12 UN FCM assemblies. A high uranium density kernel is required to keep a slow depletion rate. This can be done by using uranium nitride instead of conventional uranium oxide or oxy-carbide. A suitable solid burnable poison for FCM fuel is erbia which can be homogeneously mixed with an SiC matrix. The moderator temperature coefficient can be positive at a high soluble boron concentration with a low heavy metal inventory. The heavy metal density of a UN kernel is sufficient to constantly maintain negative temperature coefficients.

Acknowledgements

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