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Feasibility of Accident-Tolerant FCM Replacement Fuel for CANDUs

Won Jae Lee*, Chang Keun Jo and Francesco Venneri [a]
Korea Atomic Energy Research Institute, 989-111 Daedeok-Daero, Yuseong-Gu, Daejeon, 305-353, Koera
[a] *Ultra Safe Nuclear Corporation, 188 Piedra Loop, Los Alamos, NM87544, USA*
[*] *Corresponding author: wjlee@kaeri.re.kr*

1. Introduction

The Fukushima accident triggered a need to develop an accident tolerant fuel that does not lead to severe fuel failure and subsequent hydrogen release during extreme accident conditions. The "accident-tolerance" of the fuel can be achieved by high resistance to fuel failure and radioactivity release and high resistance to hydrogen generation. For enhanced accident tolerance, an innovative fuel concept, the fully ceramic micro-encapsulated (FCM) fuel based on the particle fuel concept of a gas-cooled reactor, is proposed to replace the conventional UO_2 fuel bundle of existing and advanced CANDU reactors.

In this study, the feasibility of replacing conventional UO_2 fuel bundle with the accident-tolerant FCM fuel bundle has been assessed in view of core neutronics compatibility, accident-tolerance, and fuel cycle management. From the study, it was demonstrated that the FCM replacement fuel can provide resolution to CANDU generic issues by ensuring not only enhanced accident tolerance, but also an improved fuel cycle management.

2. FCM Fuel Concept

The FCM fuel concept stems from Tri-isotropic (TRISO) coated particle fuel, historically developed for the gas-cooled reactor programs and recently re-qualified by the Next Generation Nuclear Plant (NGNP) program. The TRISO coated particle fuel has been demonstrated to have excellent radioactivity retention capability through the presence of multiple layers of ceramic coating, which are chemically stable and mechanically strong at very high temperatures and very high burnup levels [1].

As shown in Fig. 1, the FCM fuel pellet consists of TRISO particle fuels packed in a dense Silicon Carbide (SiC) matrix[2,3]. Fuel pellets are embedded in cylindrical cladding where conventional Zircaloy material is replaced with accident tolerant stainless steel (SS) 310, SiC, SiC-coated Zircaloy or FeCrAl alloy. However, the lower fissile density caused by the presence of multiple barriers needs to be compensated by introducing the higher density enriched Uranium Nitride (UN) in the fuel kernel rather than UO_2. The FCM fuel rods, which are very similar in shape to the conventional UO_2 fuel rods, can be used as replacement fuel in current LWRs and CANDUs without large modification of the reactor or the plant[4,5].

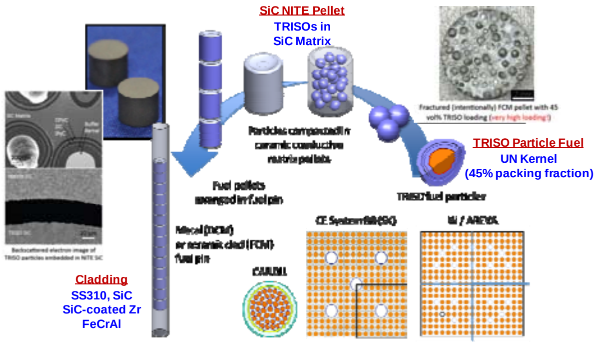

Fig. 1. FCM Fuel Design Concept

The accident tolerant features of the FCM fuel can be achieved by: 1) Resistance to meltdown, provided by the use of refractory SiC-layered TRISO particles and the SiC matrix with melting temperature around 3000°K (eutectic melting of UO_2 and Zircaloy can be excluded); 2) Resistance to radioactivity release, ensured primarily by the TRISO particle and additionally by the SiC pellet matrix (the indefinite retention capability of fission product of the TRISO particles is well proven up to 2070°K from the gas-cooled reactor experience); 3) resistance to hydrogen generation, provided by the use of alternate cladding materials, which have slower reaction kinetics with steam and much slower hydrogen generation rates than conventional Zircaloy cladding; 4) resistance to fuel thermo-mechanical degradation, provided by the highly conductive SiC pellet, which lowers the fuel centerline temperature and initial stored energy as well as the temperature gradient during normal and accident conditions.

Fission product retention by the TRISO particles and SiC matrix greatly reduces and even eliminates the fuel rod internal pressure and prevents subsequent mechanical deformation of the cladding especially during depressurization accidents such as large-break loss-of-coolant accident (LBLOCA).

In addition, the FCM fuel could provide additional benefit in spent fuel management by direct storage or deep-burning of recycled spent fuel. Also, the fission product retention capability provided by the TRISO and SiC matrix should facilitate dry storage and long-term containment of radioactivity in spent fuel management and disposal. The proliferation resistance of the FCM fuel is enhanced by the increased complexity in extracting Plutonium from the spent FCM fuel pellet and TRISO particles and by the low weapon-grade Plutonium content in the spent fuel.

3. CANDU Generic Issues

The CANDU reactor is known to have a larger inventory of Zirconium used in fuel bundle components and pressure tubes than other types of reactors. Zirconium oxidizes with water at high temperature to generate heat and hydrogen, which is the major source of safety threat in maintaining the core cooling and preventing hydrogen explosion. In addition, eutectic melting of UO_2 and Zircaloy together with continued heat generation by fission product decay and Zirconium oxidation further accelerates eutectic corium melting and large release of radioactivity[6]. Molten corium may endanger the calandria tank boundary by steam explosion once dispersed in the calandria tank. Thus, it is very important for the core and fuel to have high resistance to exothermic oxidation, eutectic melting and fission product retention.

The fuel temperature coefficient of CANDU reactors tends to become more positive at higher burn-up. Even though it does not violate current regulation and aggravate the CANDU safety, it would be better to maintain the fuel temperature coefficient negative.

In 2013, there was a significant increase in the CANDU spent fuel management burden charge in Korea. The charge was increased by more than 3 times from 4.14M KRW to 13.2M KRW per CANDU bundle. Moreover, a new storage facility is being built in order to accommodate spent fuels from Korea's four operating CANDUs. If continued operation of CANDU reactors is approved, it may require additional storage capacity[7]. So, it is very important to lessen the number of discharge fuel bundles not only for better fuel cycle economics but also for spent fuel management.

4. Feasibility Study

4.1 Reference FCM Fuel Bundle

Fig. 2 shows the CANDU FCM fuel bundle design. It adopts exactly the same dimension as the 37-element fuel bundle of conventional CANDU bundle, while the UO_2 fuel pellets are replaced with the FCM pellets and the cladding material is replaced with oxidation-resistant FeCrAl[8]. To compensate for fissile inventory reduction of the FCM fuel, 5% enriched UN kernel is introduced. Thus, of concern is the neutronic compatibility, whereas the thermal-hydraulic and mechanical compatibility is conserved.

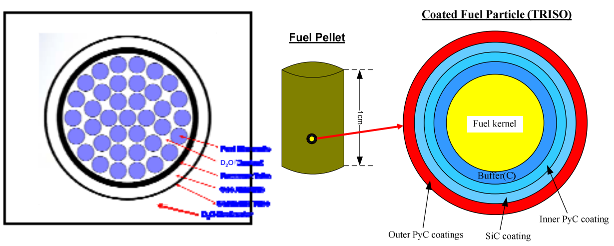

Fig. 2. CANDU FCM Fuel Bundle

4.2 Neutronic Compatibility

The neutronic compatibility of the FCM fuel bundle with the existing core has been assessed in view of core residence time, burn-up and reactivity parameters. Bundle-level lattice calculations wadere carried out using McCARD[9] with ENDF-B/VII cross section library. The enrichment of the UN kernel was selected to be 4 ~ 5% which meets manufacturing capability of light water reactor fuel. 800μm diameter of UN kernel and 42% TRISO packing fraction were used.

Fig. 3 shows the infinite multiplication factor, where initial excessive reactivity of the enriched UN is suppressed by mixed Gd_2O_3 and Er_2O_3 burnable poison. Gd_2O_3 burns faster than Er_2O_3 so that it plays a role in suppressing initial reactivity and Er_2O_3 plays a role controlling the reactivity at higher burn-up. As shown in the figure, the core residence time was increased by more than 100 days with the 5% enriched FCM fuel. The maximum burn-up of the FCM fuel was about 32 MWd/kgU, which is far below the qualified burn-up of the TRISO particle fuel.

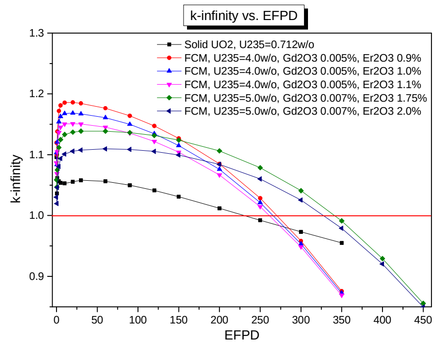

Fig. 3. Infinite Multiplication Factor vs. EFPD

Fig. 4 compares the fuel temperature coefficients. Fuel temperature coefficient of the FCM fuel is always negative over the fuel lifetime, whereas that of the UO_2 fuel becomes slightly positive at the end of the life. Coolant void coefficient remains similar each other.

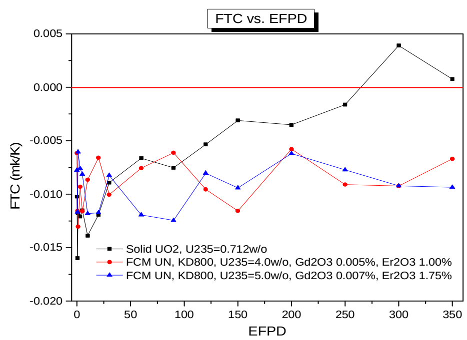

Fig. 4. Fuel Temperature Coefficient

It is shown from the analysis that the FCM fuel is neutronically compatible with the existing core. Of remarkable benefit is the longer core residence time around 100 days, thus, about 30% less feed and discharge bundles. This enables a four bundle shift, by which potential fuel failure during refueling can be reduced by limiting power peaking of feed bundles. Enhanced safety is also achieved by negative fuel temperature coefficient over the fuel lifetime.

4.3 Assessment of Accident-Tolerance

The highly conductive FCM fuel pellet, whose thermal conductivity is up to 8 times higher than that of the standard UO_2 pellet, minimizes thermo-mechanical deformation of the fuel pellet by its low temperature gradients. Unlike the UO_2 pellet, fission product retention inside the TRISO particles prevents further the mechanical deformation by fission gas migration along the UO_2 grain boundaries. The SiC matrix which is an additional fission product barrier limits fission gas pressure build-up in fuel gap. Thus, mechanical deformation of the cladding during operation as well as the swelling rupture during depressurization accidents such as LBLOCAs can be eliminated. In addition, low swelling of the FCM pellet by irradiation limits the pellet-cladding interaction at high burn-up required for longer core residence time.

Refractory FCM pellet whose melting temperature is around 3000K provides resistance to fuel melting and subsequent fission product release. This provides longer time for operator mitigation actions and limits large release of radioactivity to environment during severe accidents like station blackout.

Oxidation-resistant FeCrAl cladding material limits exothermic hydrogen generation and potential for consequent hydrogen explosion. Eutectic melting of UO_2 and Zircaloy can be excluded and the progression of corium melting can be mitigated by excluding exothermic oxidation.

From the assessment, it can be concluded that the accident-tolerance of CANDUs is greatly enhanced by replacing the core with the FCM fuel. The core integrity is ensured for a long time enough for operator's mitigation actions. It can be concluded that Fukushima-like consequence are not probable with the FCM fuel.

4.4 Fuel Cycle Management

As discussed in section 3, there are two issued related with fuel cycle management in CANDUs: the increase in the spent fuel management burden charge by more than 3 times and the expected shortage of spent fuel storage capacity in case of a continued operation. Primary concern to resolve these issues should be to lessen the number of feed and discharge fuel bundles.

It is shown from the neutronics compatibility study in section 4.2 that the FCM fuel provides longer core residence time by 100 days. Longer core residence time can be achieved by the high burn-up capability of the TRISO particles and the limited pellet-cladding interaction by the low swelling and fission product retention of the FCM pellet.

In case of 100 days increase in the core residence time, we can attain ~ 30% less fuel feed and discharge. By simple calculation, it is found that savings in the spent fuel management burden charge will be up to 82.7B KRW/yr for the four Korean CANDU reactors. Moreover, the lower number of discharge bundles should reduce a burden in current and future spent fuel storage capacity and requirements.

Fuel fabrication cost of the FCM fuel is higher by the costs required for TRISO fabrication and enrichment, even if the number of feed bundles is decreased. However, considering the saving in the spent fuel management burden charge, the overall fuel cycle cost should still be reduced. It should also be noted that the accident risk cost will be remarkably reduced by introducing the FCM fuel. It was reported that the accident risk cost ranges from 4.5 to 8.9 mils/kWh (JAEC, 2011)[10].

Another advantage obtained by introducing the FCM fuel is the reduced burden in long-term spent fuel disposal. Table 1 compares radionuclide compositions in a FCM discharge bundle and in a conventional UO_2 discharge bundle. Masses of long-lived minor actinides are significantly decreased in the FCM fuel, whereas those of fission products are slightly increased by higher burn-up. Thus, the burden imposed by long-term toxicity and decay heat by minor actinides is significantly reduced. Moreover, long-term containment of radionuclides and corrosion resistance provided by the TRISO particles and SiC matrix should facilitate the dry storage of spent fuel bundle.

Table 1. Radionuclides Composition in a Discharge Bundle

	Nuclide	Nat. UO_2 (kg/Bundle)	FCM (5%) (kg/Bundle)	Mass Reduction (%)
ACTINIDES	U-234	8.70E-04	2.14E-06	100
	U-235	4.30E-02	8.49E-02	-97
	U-238	1.93E+01	4.65E+00	76
	Np-237	5.09E-04	4.62E-04	9
	Pu-238	6.05E-05	5.14E-05	15
	Pu-239	5.32E-02	1.35E-02	75
	Pu-240	2.06E-02	5.45E-03	74
	Pu-241	4.16E-03	1.41E-03	66
	Pu-242	1.04E-03	3.92E-04	62
	Am-241	4.10E-05	1.42E-05	65
	Cm-242	9.23E-06	3.18E-06	66
	Cm-244	3.00E-06	1.05E-06	65
FP	Sr-90	2.36E-03	3.19E-03	-35
	Y-90	6.85E-07	8.71E-07	-27
	Tc-99	3.65E-03	3.85E-03	-5
	I-129	8.05E-04	5.07E-04	37
	Cs-137	5.52E-03	5.68E-03	-3

5. Technology Readiness

The FCM fuel technology is being developed under the Korea-US International Nuclear Energy Research Initiative (I-NERI) program. Design and engineering tools and methods was developed for core neutronics, thermal-hydraulics, fuel performance and safety analysis and applied in demonstrating the feasibility of

FCM replacement fuel for LWRs[4,5]. Fuel manufacturing technologies have been developed for the UN kernel and FCM pellet. FCM fuel samples were fabricated and irradiated in High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory[11]. The material properties of the FCM fuel have been characterized through pre- and post-irradiation examination tests. Further irradiation tests are planned and the scaling-up of manufacturing technologies to engineering scale is being studied. FeCrAl cladding properties were also characterized. Since these technologies are common to both LWRs and CANDUs, they are mostly applicable to the CANDU FCM fuel.

The CANDU FCM fuel adopts a 5% enriched fuel that can be accommodated by existing fuel manufacturing facilities. The bundle dimensions are exactly the same as for the conventional bundles so that the CANDU FCM fuel bundle can be easily manufactured using existing facilities. This enables the FCM fuel as a near-term deployable technology for CANDU reactors. Technology readiness level is estimated between to be 6 according to NASA guidelines[12], which is close to prototype demonstration (lead test bundle loading and irradiation). Nevertheless, for future commercialization, further irradiation of test bundles in research reactors and finally in power plants is required for fuel qualification and licensing.

6. Conclusions

The accident-tolerant FCM fuel concept is proposed for replacing the conventional UO_2 fuel bundle in CANDUs. The FCM fuel is shown to be neutronically compatible with existing core and the core residence time can be increased by more than 100 days. Accident-tolerance is remarkably enhanced by key features of the FCM fuel: it is refractory, thermo-mechanically and chemically stable, and fission product retentive. Less fuel feed and discharge obtained with the FCM fuel provide large savings in the spent fuel management burden charge and reduces the burden to the spent fuel storage facility in the long run. The smaller amount of minor actinides in the discharge bundles, together with the fission product retention and corrosion resistant features of the FCM fuel, should facilitate the long-term dry disposal of the spent fuel.

From this study, it has been demonstrated that the CANDU FCM fuel is a feasible and viable option for CANDU reactors. The technology readiness level of the FCM fuel design and manufacturing is close to a lead test bundle loading for near-term deployment.

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