BgNS TRANSACTIONS volume **20** number 2 (2015) pp. 121–123

Neutronic Comparison of Proposed Claddings for Accident Tolerant Fuel with Zirconium Based Cladding in PWRs

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Abstract. Accident tolerant fuels are expected to maintain safety for longer periods of time with respect to standard PWR fuels in the case of design bases and beyond design bases accidents while maintaining good operational characteristics during normal operations. There are several new concepts to consider such as improving oxidation resistance and/or strength of current Zirconium alloy, replacing Zirconium with higher strength and/or oxidation resistance material, and introducing alternative fuel forms. In the meantime, fuel burnup, fuel pin lifetime, maximum operating temperature, clad failure mechanisms, and corrosion rates must be considered in the more detailed analysis. In this study, 304 stainless-steel, FeCrAl, and SiC are selected as new clad materials and their neutronic performances are compared with performance of standard Zirconium alloy clad. Non-linear reactivity model and MONTEBURNS code are used for calculations. Results show that SiC results in longer fuel cycle length among other cladding materials without changing any operational and fuel characteristics. On the other hand, the other materials considered in this study need reevaluation of enrichment and/or geometrical design parameters.

Keywords: accident tolerant fuel, burnup, MONTEBURNS

1 Introduction

Fuels with enhanced accident tolerance are those that, in comparison with the standard UO_2 – Zirconium (Zr) system, can tolerate loss of active cooling in the core for a considerably longer time period (depending on the LWR system and accident scenario) while maintaining or improving the fuel performance during normal operations [1]. This can be achieved either providing improvements to current Zircaloy cladding or changing cladding material (oxidation resistant structural alloys, SiC, refractory alloys etc.), or creating completely new fuel forms (fuels having high density and thermal conductivity (e.g., monolithic nitrides or oxides containing high-conductivity second phases) and dispersed/inert matrix fuel forms where the fission products would be contained within discrete, isolated fuel particles embedded within a non-fissile matrix (e.g., fully ceramic microencapsulated fuel (FCM) forms)) [2]. The new designs should be compatible with current nuclear power plants in terms of operations and fuel cycle and they should provide good economic performance.

In this study, the effect of introducing new cladding material without changing any operational and geometrical parameters on neutronic performance of the fuel was analyzed by using MONTEBURNS code [3]. MONTEBURNS is a Monte Carlo burnup code that links the Monte Carlo transport code MCNP [4] with the radioactive decay and burnup code ORIGEN2 [5]. The geometry is modeled with MCNP. It calculates one-group cross sections and fluxes that are used by ORIGEN2 in burnup calculations and provides criticality and neutron economy information if requested. After performing burnup calculations using ORIGEN2, MONTEBURNS passes isotopic compositions of materials back to MCNP to begin another burnup step. The standard PWR fuel pin geometry with Zircaloy clad was selected as reference case and the effect of changing clad material to 304 stainless-steel (SS304), FeCrAl, and SiC on cycle lifetime and burnup is examined.

2 Results and Discussions

In order to analyze the effect of different cladding materials on core neutronics, a PWR pin cell geometry shown in Figure 1 was modeled with MCNP5 code. The pin cell is composed of 4.9% enriched UO_2 fuel pellet with density of 10.47 g/cm^3. There is a gap between fuel pellet and cladding and water is both coolant and moderator. The pin cell with Zircaloy clad was selected as reference case. It was assumed to be in a standard PWR that produces constant power of 38.33 MW per metric ton of Uranium (MTU) for 1420 effective full power days (18-month cycle). Four

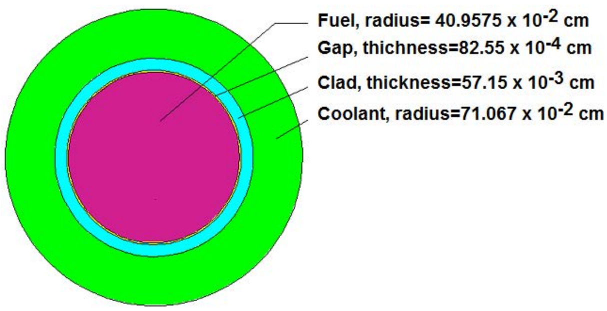

Figure 1. Geometry of PWR pin cell.

Table 1. Cladding material compositions in weight percent

Cladding	Fe	Cr	Zr	Al	Ni	Sn	Mn	Mo	Si	C
Zircaloy	0.15	0.1	98.26	—	—	1.49	—	—	—	—
SS304	71.35	18.9	—	—	8.35	—	0.7	0.27	0.42	—
FeCrAl	75.0	20.0	—	5.0	—	—	—	—	—	—
SiC	—	—	—	—	—	—	—	—	50	50

burnup simulations were performed with MONTEBURNS code while keeping all dimensions the same, but changing only the cladding material from Zircaloy to 304 stainless-steel, FeCrAl, and SiC respectively. The composition of clads used for calculations is summarized in Table 1.

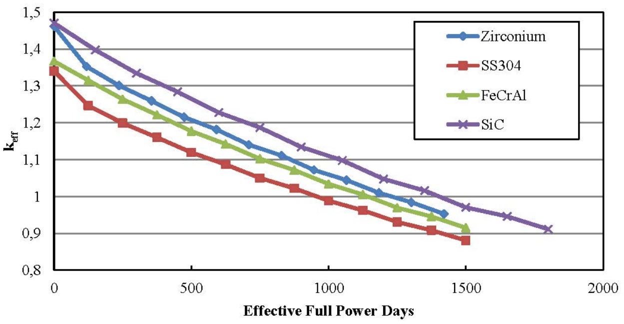

Figure 2. The variation of k_{eff} with time for proposed fuel designs.

Figure 2 shows the variation of k_{eff} (effective multiplication factor) with time for 4 different cladding materials. When compared with the reference case, the highest decrease in k_{eff} occurs for 304 stainless-steel cladding case. The increase in plutonium breeding in the core due to harder spectrum of proposed cladding design is the cause of this reduction. Only increase in k_{eff} occurs for SiC cladding case due to reduction in neutron absorption, since the absorption cross section of SiC is 0.086 barn compared to 0.20 barn of Zircaloy. Similar deductions are reported by George et al. [6].

In order to calculate the discharge burnup it is necessary to know leakage reactivity of the system. The method described in Driscoll et al. [7] is used in this study and it assumes that fuel cycle is divided into three equally sized batches and there are equal power sharing factors for each batch. Equation (1) is then used to calculate leakage reactivity of the system.

$$\frac{\rho(B_1) + \rho(B_2) + \rho(B_3)}{3} - \rho_L = 0\,, \qquad (1)$$

where ρ_L is the leakage reactivity of the system, B_i is the burnup of batch i, and $\rho(B_i)$ is the reactivity at burnup B_i. The relation between burnup of the each batch is given in Eq. (2).

$$B_i = i \times B_1 \qquad i = 2,\, 3. \qquad (2)$$

By applying Eq. (1) and Eq. (2) on reference case, the leakage reactivity of the system was calculated as 6747 pcm. The method described in detail by Özdemir et al. [8], that uses non-linear reactivity model and variation of reactivity with burnup, is used to calculate discharge burnup of proposed fuels. The variation of reactivity with burnup

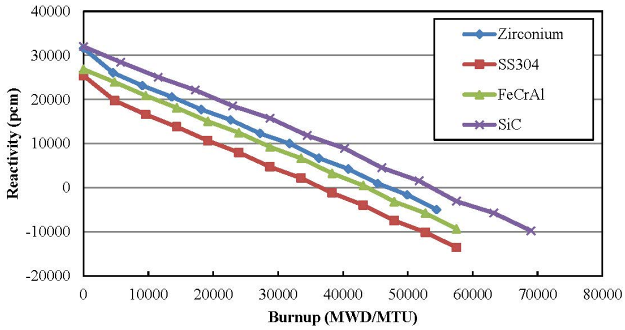

Figure 3. The variation of reactivity with burnup for proposed fuel designs.

for proposed designs from MONTEBURNS is shown in Figure 3. SiC cladding leads to highest burnup among other cladding materials. By using Eq. (1) and Eq. (2), and data in Figure 3 the discharge burnup of the fuel with proposed cladding materials were calculated and results are reported in Table 2. It is shows that length of the fuel cycle decreases when Zircaloy cladding is replaced with either 304 stainless-steel (29% reduction) or FeCrAl (10% reduction), but increases when it is replaced by SiC (17% increase).

Table 2. Calculated discharge burnup of proposed designs

Cladding	Discharge Burnup (MWD/MTU)	Effective Full Power Days
Zircaloy	54528	1420
SS304	38538	1005
FeCrAl	49171	1282
SiC	63907	1667

3 Conclusions

The impact of changing standard PWR cladding from Zircaloy to 304 stainless-steel, FeCrAl or SiC in order to create accident tolerant fuel on neutronic performance of the fuel was analyzed with MONTEBURNS code. The calculations showed that there is a reduction in k_{eff} at the end of fuel cycle for 304 stainless-steel and FeCrAl claddings, 304 stainless-steel being the worse, and there is an increase in k_{eff} for SiC cladding. As an expected outcome of this, cycle lifetime of fuel with SiC claddings longer than the fuel with other cladding options. Therefore, the fuel with cladding materials considered in this study except SiC need reevaluation of either enrichment or geometrical design parameters to reach same burnup level as standard UO_2-Zr based fuel.

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