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The safety analysis of a small pressurized water reactor utilizing fully ceramic microencapsulated fuel

Jinfeng Huang, Ning Li, Yaoli Zhang *, Qixun Guo, Jian Zhang

Department of Nuclear Engineering and Materials, College of Energy, Xiamen University, Xiamen 361102, China

HIGHLIGHTS

- Some design optimizations are taken to achieve the acceptable cycle lengths.
- Suppressing the excess reactivity, the core power distributions and reactivity coefficients are performed.
- The steady state and transient state analyses are carried out.

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ABSTRACT

For post-Fukushima nuclear power plants, accident-tolerant fuel (ATF) is strongly desired in order to prevent radioactive release in the event of a severe accident. The Fully Ceramic Microencapsulated (FCM) fuel is one of these materials. The neutronics and thermal hydraulics analysis of small pressurized water reactor (PWR) utilizing FCM fuels needs to be carried out to demonstrate this fuel performance. In this study, first, a three dimensional full core model of a small PWR design is developed to assess the cycle lengths and power distribution. In order to achieve the acceptable cycle lengths, some design optimizations are taken, including higher TRISO particle packing fraction, higher enrichment and using higher density fuels. The results demonstrate that the acceptable cycle lengths can be achieved after this design optimizations. The results reveal that the cycle lengths can be improved to about 550 days after using the 19.9 w/o enrichment fuels with UO_2 fuel kernel, and the cycle lengths can be maintain about 800 days with UN fuel kernel due to the higher density than UO_2 fuel kernel. Then, suppressing the excess reactivity, the core power distributions and reactivity coefficients are performed to prepare for thermal hydraulics analysis.

The steady state and transient state analysis for LOCA is carried out using the best estimate system code RELAP5. For the conventional UO_2 fuel, fission product releases simultaneously when the cladding fails. But for the FCM fuel, the radioactive material can be contained in the fuel pellet even after the cladding failure since enveloping the TRISO particles within a dense SiC matrix provides multiple barriers to fission product release. Consequently, although the Zircalloy cladding fails, there is still 3500 s available for operator actions before the start of FCM fuel melting occurs even through the SB-LOCA occurring without ECCS, and there is still 1443 s available even through the LB-LOCA occurring without ECCS. The results of the accident analysis without ECCS would be useful in understanding cladding and fuel failure progression and could provide guidelines in establishing detailed accident management procedures to design the proper ECCS in the future.

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1. Introduction

The Fukushima Daiichi nuclear disaster revealed the disadvantage of traditional LWR UO_2 fuel-Zircalloy cladding system, in which the fuel rods were meltdown. For post-Fukushima nuclear power plants, accident-tolerant fuel (ATF) is strongly developing to prevent radioactive release in the event of a severe accident (Younker and Fratoni, 2016; Spencer et al., 2016; Brown, 2017). The Fully Ceramic Microencapsulated (FCM) fuel is one of these ATF materials which replace traditional UO_2 pellets fuel in LWRs to make the LWRs safer and may eradicate the nuclear disaster (Terrani et al., 2012; Snead et al., 2014; Pope et al., 2012).

In the framework of the Advanced Fuels Campaign, Brown (Brown et al., 2013) investigated a neutronic evaluation of the utilizing FCM fuel in advanced PWRs, and the Westinghouse AP1000

* Corresponding author.
E-mail address: zhangyl@xmu.edu.cn (Y. Zhang).

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was selected as the reference core for analyzing the operational and safety performance of FCM fuels in PWRs.

The cycle length for FCM-fueled LWR concepts with current assembly geometries was evaluated by R. Sonat Sen (Sonat Sen et al., 2013). The study showed that a naive use of UO_2 results in cycle lengths too short to be practical for existing LWR designs and operational demands. The basic parameters are taken from a typical modern PWR, specifically the AREVA EPR design and the assumed power rating is 4500 MWt.

A conceptual core design of a 350MWt PWR using FCM fuel concept was analyzed by Xiang Dai (Dai et al., 2014). Due to an extreme larger core geometry changes, a six-year core cycle length can be achieved without refueling and soluble boron free operation.

Preliminary analyses regarding the initial stored energy and accident tolerant performance were carried out by Ji-Han Chun (Chun et al., 2015) for the scoping of various cladding material candidates. In order to demonstrate the accident tolerance of the FCM fueled core, a loss of flow accident scenario was selected for a departure-from-nucleate-boiling evaluation, and large-break loss of coolant accident (LBLOCA) scenario for peak cladding temperature margin evaluation through a preliminary scoping analysis with the reference OPR-1000 UO_2/Zr fueled core. The analysis results show that the safety of the FCM fueled core meets the preliminary safety criteria with a sufficient margin.

The effect of selected candidate ATF systems on the response of a PWR under extreme LBLOCA and extended station blackout accident conditions were studied by Xiaoli Wu (Wu et al., 2015). The reference nuclear power plant adopted is the Chinese improved three-loop PWR CPR1000 with U-tube steam generator design. Among the ATF systems considered here, the FCM-SiC system shows more distinguished accident-tolerance.

For a thermal analysis of the FCM fuel with a high heterogeneity, a two-temperature homogenized thermal-conductivity model was applied by Yoonhee Lee (Lee and Zin Cho, 2015). This model provides separate temperatures for the fuel-kernels and the SiC matrix. In their study, coupled with a neutron diffusion model, a FCM fuel-loaded reactor core is analyzed via a two-temperature homogenized thermal-conductivity model at steady- and transient-states. There were 9 assemblies in the core model, with a total thermal power of 70.0 MW.

Recently, the development of its ACPR50S (50 MWe) reactor design proposed by China General Nuclear Power Group had been approved by China's National Development and Reform Commission for innovative energy technologies. Replacing the traditional UO_2 pellet utilized in ACPR50S into FCM fuels can enhance the safety of the reactor due to the excellent characteristic of containing the fission production.

However, the safety analysis of small PWR utilizing FCM fuels needs to be carried out to demonstrate this fuel performance. In this study, a three dimensional full core model of the small reactor design is developed to assess the neutronic behavior of the reactor core. In order to achieve the acceptable cycle lengths, some design optimizations are taken, including higher TRISO particle packing fraction, higher enrichment and using higher density fuels. The results demonstrates that the acceptable cycle lengths can be achieved after this design optimizations taken. Finally, a RELAP5 nodalization of the small PWR is developed to perform the safety analysis without emergency core cooling system (ECCS).

2. Core models and methodology

This study simulates every fuel rod in the core and every kernel in the fuel rod explicitly using the MCNP4C in order to take the double heterogeneity existing in small PWR utilization FCM into consideration. The MCNP4C is a Monte Carlo neutron transport code and does not perform the burnup calculations. Therefore, the burnup calculation is carried out MCNP4C coupled ORIGEN code. A new MCNP-ORIGEN linkage program named as MOC-BN has been developed to provide the depletion capability for the MCNP4C. The results of MOC-BN are in very good agreement with other computational results especially with the MCNPX2.6. Assembly power fractions are also calculated by MOC-BN and passed to RELAP5 code where parameters of the hot channel and other channels are calculated.

The RELAP5 code is a versatile and robust system analysis code based on a one-dimensional two-fluid model for two-phase flows. The RELAP5 code is used to perform the thermal hydraulics analysis during the normal and accident conditions. It has been extensively used in the design and safety analysis of liquid metal, gas and water cooled reactor cores. It is a very powerful tool because it can be applied to the most complicated fuel configuration with relative ease.

3. Results and discussion

3.1. Core physics modeling

Fig. 1 shows the structure of FCM fuel rod. The fuel pellets which consist of TRISO particles embedded into SiC matrix are loaded in Zircalloy cladding. Table 1 gives parameters for the designed small PWR assembly and core (Fig. 2). The assumed power is 200 MWth and the number of 17 × 17 fuel assemblies are 37. Assembly pitch and fuel pellet diameter are similar to typical modern PWR, but the average linear power and average power density is about 50% of typical modern PWR (Sengler et al., 1999) to enhance the safety margin and prolong the cycle lengths.

The study (Sonat Sen et al., 2013) shows that a naïve use of UO_2 results in cycle lengths too short to be practical for existing LWR designs and operational demands. But acceptable cycle lengths can be achieved through increasing fissile inventory, and some design optimization can be taken, for examples, higher TRISO particle packing fraction, higher enrichment and using higher density fuels (U_3Si, UN).

In order to show the different with TRISO particles packing fraction, the first generation model was based on a single cubic (SC) lattice distributed within a fuel rod, but the TRISO particles packing fraction is low. Then the body-centered cubic (BCC) (Fig. 3) lattice is designed to enhance the TRISO particles packing fraction. Fig. 4 shows that different between SC and BCC lattics loading within the fuel rods. It is clear that the effective full power days (EFPDs) can be prolonged from 30 days to 260 days after SC lattics are changed to BCC lattics. However, the cycle lengths could not acceptable since it is too short for industrial use. Therefore, the

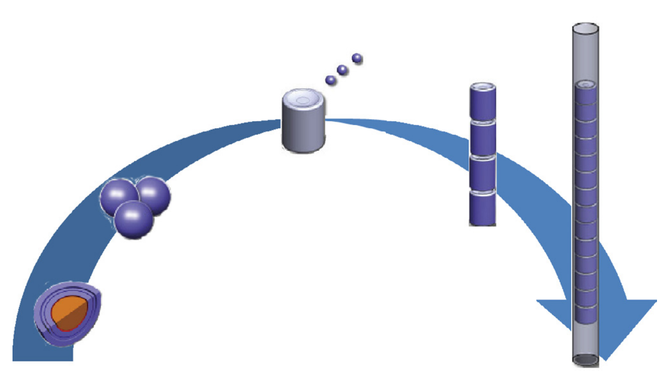

Fig. 1. The structure of FCM fuel rod.

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