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The excess reactivity management in small pressurized water reactor utilizing fully ceramic microencapsulated fuel

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ABSTRACT

After Fukushima Daiichi nuclear disaster, different techniques to overcome the weaknesses of pressurized water reactor (PWR) were developed, such as a change of the cladding and fuel materials. The Fully Ceramic Microencapsulated (FCM) fuel is one of those potential materials to replace traditional UO_2 pellets fuel to make PWR safer.

In this paper, a neutronics study has been performed to apply burnable poison (BP) for an excess reactivity management in a 200 MWt small PWR adopted soluble boron free (SBF) concept. In this core design, fuel enrichment is set as 19.9 w/o to get long enough cycle length due to the low packing faction of FCM fuels. As a result, the excess reactivity control of the core would be huge at the beginning of core life. In order to suppress excess reactivity efficiently, burnable poison such as Pu-238, Integral Fuel Burnable Absorber (IFBA) and Wet Annular Burnable Absorber (WABA) were evaluated for a cycle in terms of the major core performance parameters such as the suppressing excess reactivity, shutdown margin, and core cycle length. MCNP4C and ORIGEN were used as a tool to perform the results. It has been demonstrated that the burnup reactivity swing over a long cycle period can be reduced from 50,000 pcm to about 20,000 pcm due to utilizing different type burnable poison. It is shown that combinations of burnable poison with control rods make it possible to reduce excess reactivity and get enough shutdown margin during the core life for soluble boron free operation.

1. Introduction

Most of the pressurized water reactors (PWRs) are operating by UO_2 fuel pellets as nuclear fuel in the world at present. Although the fuel pellets are utilized widely, there are still some defects in the high temperature, such as a lower thermal conductivity due to higher centerline temperature.

After Fukushima Daiichi nuclear disaster, different techniques aiming at increasing response time following large brake loss of coolant accidents (LBLOCAs) in LWRs were developed, such as a change of the cladding and fuel materials. The Fully Ceramic Microencapsulated (FCM) fuel is one of these materials which may replace traditional UO_2 pellets fuel in PWRs to make the PWRs safer.

The FCM fuel consists of TRISO particles embedded in an impervious silicon carbide matrix, and the silicon carbide matrix in the FCM pellet offers the advantages of environmental stability, radiation damage resistance, good thermal conductivity, and proliferation resistance. Moreover, enveloping the TRISO particles within a dense SiC matrix provides multiple barriers to fission product release. Due to the excellent characteristics of FCM fuel, after the concept was proposed, many studies have been carried out.

In the framework of the Deep Burn (DB) project, once-through burning of FCM fuel in Light Water Reactors (LWRs) was investigated by Brown (Brown et al., 2013a,b; Michael et al., 2012) for core physics. His study is a neutronic evaluation of the use of FCM fuel in advanced PWRs, and the Westinghouse AP1000 was selected as the reference core for analyzing the operational and safety performance of FCM fuels in PWRs.

The work by Terrani (Terrani et al., 2012a; Terrani et al., 2012b; Terrani and Kiggans, 2012) showed that with marginal redesign, significant gains in operational reliability and accident response margins could be potentially achieved by replacing conventional oxide-type LWR fuel with microencapsulated fuel forms.

Snead (Snead et al., 2014) studied the fuel and material

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performance at LWR relevant conditions. The irradiation behavior of surrogate microencapsulated fuel and the nano-phase powder based sintered SiC matrix have been carried out to determine material stability.

R. Sonat Sen (R. Sonat Sen et al., 2013) estimated the cycle length for FCM-fueled LWR concepts with current assembly geometries. The study showed that a naive use of UO_2 (even up to 20 w/o enrichment) 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 and the number of 17 × 17 fuel assemblies is 241.

Xiang Dai (Xiang et al., 2014) discussed a conceptual core design of a 350MWt small PWR using FCM fuel concept. Due to an extreme larger core geometry changes, a six-year core cycle length can be achieved without refueling and soluble boron free operation. In the core, Pu-240 is mixed within fuel kernel in some assemblies, and Gd_2O_3-UO_2 rods are loaded in other assemblies, which combined together hold-down reactivity efficiently.

Recently, the development of its ACPR50S reactor design proposed by China General Nuclear Power Group (CGN) had been approved by China's National Development and Reform Commission as part of the 13th Five-Year Plan for innovative energy technologies. The 200 MWt (50 MWe) reactor utilizing traditional UO_2 pellet has been developed for the supply of electricity, heat and desalination and could be used on islands or in coastal areas, or for offshore oil and gas exploration. Therefore, in this work, a detailed evaluation of the compact small PWR reactor core of 200MWt is designed and also can be applied in ACPR50S to enhance the safety of it through replacing the traditional UO_2 pellet into FCM fuels.

However, applying FCM fuel in small pressurized water reactor faces some special challenges. On one hand, the effective fissile material inventory is significantly reduced in FCM fuel loading core due to the volume in an FCM fuel rod being occupied mainly by the silicon carbide matrix and the layers of pyrolytic carbon (PyC), carbon and SiC within the TRISO fuel particles. As a result, directly using FCM enrichment fuel in conventional PWR design can hardly reach the acceptable long core cycle lengths purpose (R. Sonat Sen et al., 2013; Michael et al., 2012). Consequently, higher enrichment fuel (even up to 20 w/o enrichment) may be used to get long core life purpose. On the other hand, the Soluble Boron Free (SBF) operation concepts are more popular in small PWR because it makes the plant simpler and better economic. Unfortunately, all of such above measurements make reactivity difficult to control over the entire fuel cycle.

Consequently, a detailed study of utilizing burnable poison for small PWR was needed to be carried out to manage the excess reactivity for the original geometry in ACPR50S. In this work, a detailed evaluation of the two different compact small PWR reactor core configuration of 200MWt is designed. The behavior of minimized excess reactivity swing during the core life has been assessed. For this purpose, burnable poison such as Pu-238, Integral Fuel Burnable Absorber (IFBA) and Wet Annular Burnable Absorber (WABA) were evaluated for a cycle in terms of the major core performance parameters such as the shutdown margin, burnup reactivity swing, and core cycle length.

2. Core models and methodology

The work performed by R. Sonat Sen (R. Sonat Sen et al., 2013) shows that a naive use of FCM fuel (even up to 20 w/o enrichment) can not achieve the acceptable cycle lengths for existing PWR designs and operation. The demanding of the cycle lengths can be accomplished through many methods, including larger fuel kernel sizes, higher density fuels and higher particle packing fraction. Up to now, the TRISO particles were modeled in a static hexagonal matrix, and recognized highest packing fraction is 44% (R. Sonat Sen et al., 2013; Ammar Khan et al., 2014). This paper adopts the body centered cubic lattice pattern to model fuel kernels in the fuel rod (see Fig. 1), which improves the packing fraction to 54.88%. Burnable absorber and control rods are combined to minimized reactivity swing for containing 19.9 w/o enriched uranium dioxide.

Table 1 shows the parameters of the designed small PWR assembly and reactor core (see Fig. 2). The assumed power is 200 MWt and the number of 17 × 17 fuel assemblies is 37. Assembly pitch and fuel pellet diameter is 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.

This study simulates every fuel rod in the core and every kernel in the fuel rod explicitly using MCNP4C code in order to treat the double heterogeneity of the FCM fuels. The neutron cross-sections (ENDF/B-VI) were applied to calculate the effective multiplication factor (k-eff) and analyze the effect of burnable poisons, and nuclear data used in MCNP calculations were generated from the makxsf code. The burnup calculation is performed by MCNP4C coupled ORIGEN code since MCNP4C as a Monte Carlo transport code does not perform the depletion calculations. A new MCNP-ORIGEN linkage program named as MOC-BN has been developed to provide the depletion capability. The results of MOC-BN are in very good agreement with other computational results especially with the MCNPX2.6.

3. Results and discussion

3.1. The first core configuration for analysis

3.1.1. Addition of Pu-238 in TRISO fuel particle

The new idea of introducing Pu-238 into fuel to hold-down excess reactivity for conventional PWR is developed by Soon

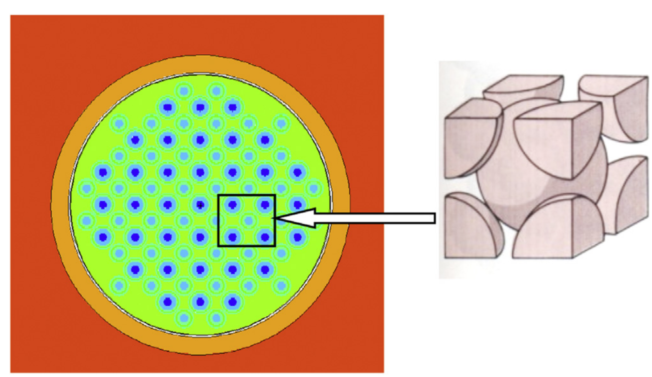

Fig. 1. TRISO particles arrangement body centered cubic lattice pattern within a fuel rod.

Table 1
Characteristics of the small PWR assembly and core initially analyzed.

Parameter	Value
Reactor thermal power (MWt)	200
Number of fuel assemblies	37
Active fuel height (m)	2.5
Assembly pitch (cm)	21.04
Number of fuel pins per 17 × 17 assembly	268
Fuel pellet diameter (mm)	8.49
Average linear power (kW/m)	8.067
Average power per unit volume of core (MWt/m^3)	49.03