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Neutronic analysis of fuel pin design for the long-life core in a pressurized water reactor

Hoang Van Khanh [1,*], Tran Vinh Thanh[2], Cao Dinh Hung[1], Pham Nhu Viet Ha[1]

[1]Institute for Nuclear Science and Technology,
179 Hoang Quoc Viet street, Nghia Do ward, Cau Giay district, Ha Noi city
[2]Vietnam Agency for Radiation and Nuclear Safety,
113 Tran Duy Hung street, Trung Hoa ward, Cau Giay district, Ha Noi city
[*]E-mail: hvkhanh21@gmail.com

Abstract: This work presents the neutronic analysis of fuel design for a long-life core in a pressurized water reactor (PWR). In order to achieve a high burnup, a high enrichment U-235 is traditionally considered without special constraints against proliferation. To counter the excess reactivity, Erbium was selected as a burnable poison due to its good depletion performance. Calculations based on a standard fuel model were carried out for the PWR type core using SRAC code system. A parametric study was performed to quantify the neutronically achievable burnup at a number of enrichment levels and for a numerous geometries covering a wide design space of lattice pitch. The fuel temperature and coolant temperature reactivity coefficients as well as the small and large void reactivity coefficients are also investigated. It was found that it is possible to achieve sufficient criticality up to 100 GWd/tHM burnup without compromising the safety parameters.

Keywords: PWR *fuel pin design, long-life core, neutronic analysis.*

I. INTRODUCTION

This paper reports a summary of the neutronic analysis part of a project, the objective of which is to approach the long-life core in a small pressurized water reactor (PWR) with uranium oxide fuel. As it is mentioned in the previous researches, the high fuel burnup is a rather essential issue in new reactor concepts. It raises a possibility of achieving the long-life core that is comparable to a reactor lifetime. The long-life core, i.e., core with long fuel residence time, would avoid on site spent fuel management, reduce plutonium inventory, thus, improving economic benefits [2], [3], [4].

For once-through burning uranium oxide fuel (UO_2) in light water reactors, the long-life core requires the nuclear fuel with high U-235 enrichment. As is known that the nuclear fuel that uranium with U-235 fraction less than 20% (low enrichment uranium, LEU) is not treated as a nuclear material for direct use in weapon manufacturing that gives a upper limitation for challenging the uranium fuels for the long-life core. The main idea behind the present paper is to use LEU as a once-through burning uranium oxide fuel in a pressurized water reactor that requires no expanding beyond the present day fuel cycle technology that the fuel is burnt up to 100 GWd/tHM [5].

The intrinsic issue for the long-life core with once-through burning high U-235

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enrichment fuel is initial high reactivity excess. It opens a necessary application of burnable poisons (BP) to reduce initial high reactivity excess as in previous studies [6], [7], [8], [9], [10]. Among these mentioned researches, it is found that selected Erbium as a most promising candidate for the long-life core with once-through burning. After the Fukushima Daiichi nuclear accident in 2011, accident tolerant fuel (ATF) systems have attracted significant attention to mitigate the consequences of a future severe accident, by better retaining fission products and/or providing operators more time to implement emergency measures of commercial light water reactors. The desired ATF needs to against a loss of cooling for a considerably long period, and improve fuel performance while enhancing fuel safety at normal operation. One way to meet these demands is to develop a new fuel with high thermal conductivity. Another way is to develop enhanced strength and ductility ATF cladding mitigate against severe accidents [11]. As a results of the previous investigation, [12], the cladding of SiC could meet lifetime requirements even with a 0.1% reduction in enrichment. Because of these findings, the Erbium is selected as burnable poison and SiC is chosen as cladding material in present study. The main subject of this paper is to presents the neutronic analysis of fuel design for a long-life core in a pressurized water reactor.

II. METHODOLOGY AND CALCULATIONAL MODEL

The neutronic analysis is performed using SRAC code system [13]. The SRAC system is designed to perform neutronics calculation for various types of thermal reactors. This system can covers production of effective microscopic and macroscopic group cross-sections, and static cell and core calculations including burn-up analyses. The burnup chain data used is based on a thermal fission energy scheme, while the nuclear data library of JENDL-4.0 [14]. In this paper, neutronic study investigation is limited to infinite pin cell calculation with material, temperature, and fuel cell characteristics listed in Table I.

Table I. Parameters of the unit cells

Parameters	Reference	New design
Fuel diameter	0.81915	0.81915
Clad inside diameter, [cm]	0.83566	0.83566
Clad outside diameter, [cm]	0.94996	1.03566
Lattice pitch, P, [cm]	1.25984	Varialbles
P/D, [-]	1.32620	Varialbles
Equivalent pin pitch, [cm]	--	1.31181
Equivalent P/D, [cm]	--	1.26664
Linear heat rate, [W/cm]	176.53	
Average coolant temperature in core, [K]	576.50	
System pressure, nominal, [Mpa]	15.51	
Average temperature for fuel, [K]	950.00	
Average temperature for clad, [K]	607.00	

The reference geometry and specific power assumed for fuel cells are given in Table I. The fuel cell is square in design and composed of four regions: fuel pellet (innermost region), gap, cladding, and coolant (outer most region). Cladding covers the fuel to form a fuel pin. The gap between the fuel and the cladding is filled with helium gas to permit better thermal contact between the fuel and the cladding. The data for the reference unit cell correspond to the Westinghouse PWR fuel pin design that loaded fuel of the 4.45 % wt. U-235 enrichment. As described in the previous section, in order to enhance strength and ductility ATF cladding mitigate against severe, SiC is selected as the cladding material as in [15]. For the long-life core, especially with a burnable poison, it is reasonably expected a hardener neutron spectrum and higher pressure of gaseous fission products compared to the reference case. Thus, for the high burnup, up to 100 GWd/tHM, the fuel would experience in a condition of high porosity. In this study, the porosity of the fuel is chosen of 15%.

III. CALCULATED CHARACTERISTICS

The analysis of each unit cell includes the calculation of the achievable burnup and of reactivity coefficients of a once-through burning fuel. The reactivity coefficients examined are the fuel temperature coefficient of reactivity (FTC), the coolant temperature coefficient of reactivity (CTC), and the small and large void coefficients of reactivity (SVRC and LVRC). The FTC is evaluated by increasing the fuel temperature by 100 K - from 950 to 1050 K. For the CTC the water temperature is increased from the nominal value of 576.50 K by 10 K to 586.50 K. In case of void coefficients, both small and large, the temperature of the water is left unchanged while the density of the moderator is reduced by, respectively, 5 % or 90 %.

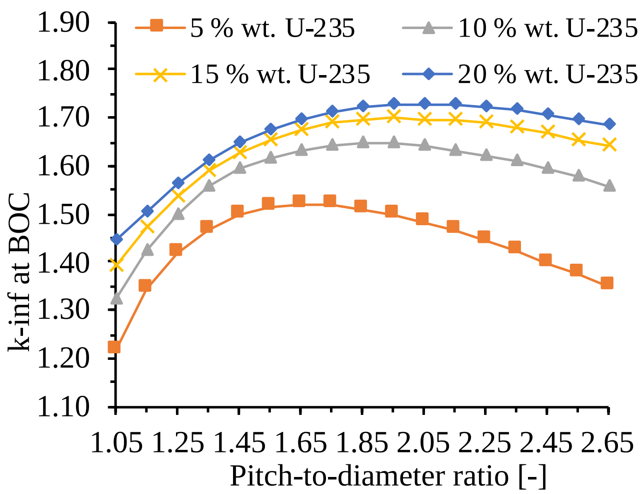

Fig. 1. k-inf at BOC as a function of P/D

The investigations in this study are U-235 enrichment, ranging from 5 to 20 % and lattice pitch-to-diameter ratio (P/D) ranging from 1.05 to 2.65. Calculated for each of the cases studied are the achievable once-through burnup and the reactivity coefficients along the fuel life without soluble boron in the water. The achievable burnup was assumed based on combining of negative reactivity coefficients and infinite multiplication factor (k-inf) value at the end of cycle (EOC) is 1.05.

IV. RESULTS

Figure 1 shows the initial k-inf value as a function of P/D. Table 2 summarizes selected characteristics calculated for fuel cell with U-235 enrichment, ranging from 5 to 20 % and lattice P/D ranging from 1.05 to 2.65. Increasing the U-235 enrichment results in increasing of both maximum achievable burnup and k-inf value at begin of cycle (BOC). Higher U-235 enrichment in fuel gives larger P/D ranging to achieve the high burnup. This is because of the increase of fissile isotope, U-235, in the heavy metal inventory. It is found that the fuel of ≥15 % wt. U-235 enrichment is potential for a long-life core design. The required P/D ranging is from 1.25 to 1.85 and 1.15 to 1.96 for fuel cell with, respectively, 15 and 20 % wt. U-235 enrichment. The potential maximum achievable burnup would reach up to 120 GWd/tHM.

Table II. Fuel cell selected characteristics versus P/D and U-235 enrichment

Parameters	**Values or conditions**		
Enrichment, [wt. %]	**P/D for burnup > 100 GWd/t**	**Max. burnup, [GWd/t]**	**k-inf at BOC, [-]**
4.45	--	30.0	1.3950
5.00	--	40.0	--
10.00	--	80.0	--
15.00	1.25-1.85	> 120	1.5368-1.6959
20.00	1.15-1.95	> 120	1.5062-1.7265

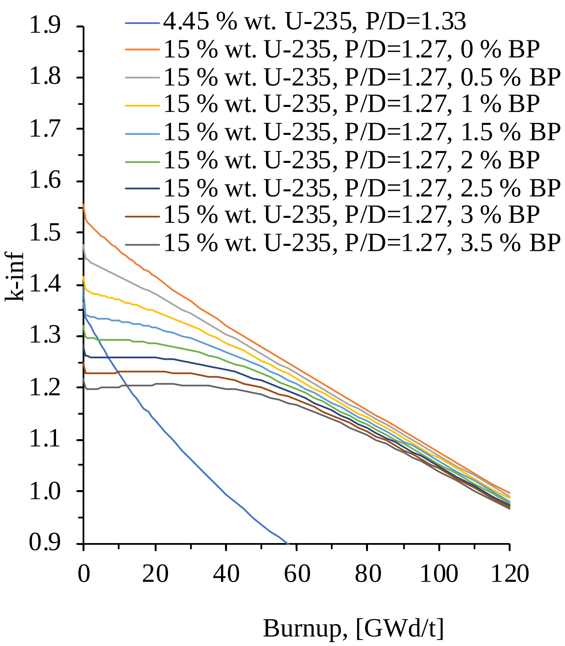

Fig. 5. Effect of BP addition to fuel cell on reactivity

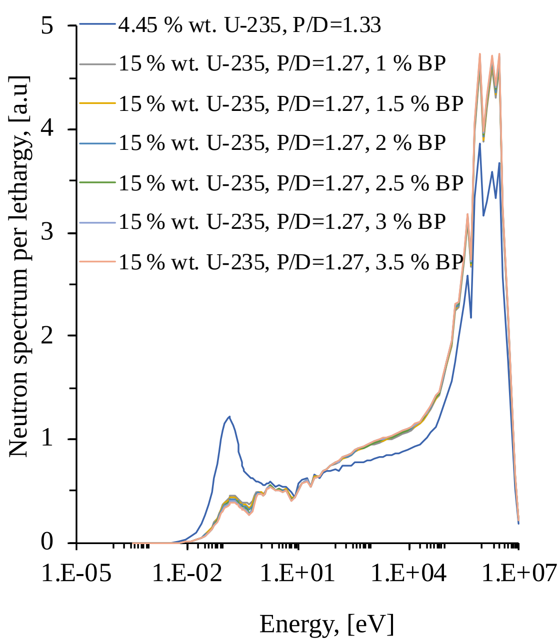

Fig. 6. Effect of BP addition to fuel cell on neutron spectra

Figure 2 shows a comparison of k-inf evolution as a function of burning time for the some cases examined. Figure 3 compares the BOC neutron spectrum of some studied fuel cells. With the same U-235 enrichment, increasing P/D value makes the spectrum is softer, and reduces the k-inf along fuel cycle. Table 2 and Fig. 2, based on pin cell calculations of the lattice with P/D ranging from 1.05 to 2.65, shows the possibility to burn the fuel of ≥15 % wt. U-235 enrichment up to 120 GWd/tHM, 1.05 infinite multiplication factor assumed at the EOC. That is higher than the targeted burnup value, 100 GWd/tHM, in this study. But the initial k-inf values are higher than that of the reference fuel cell as seen in Table II, Figure 1, and Figure 2.

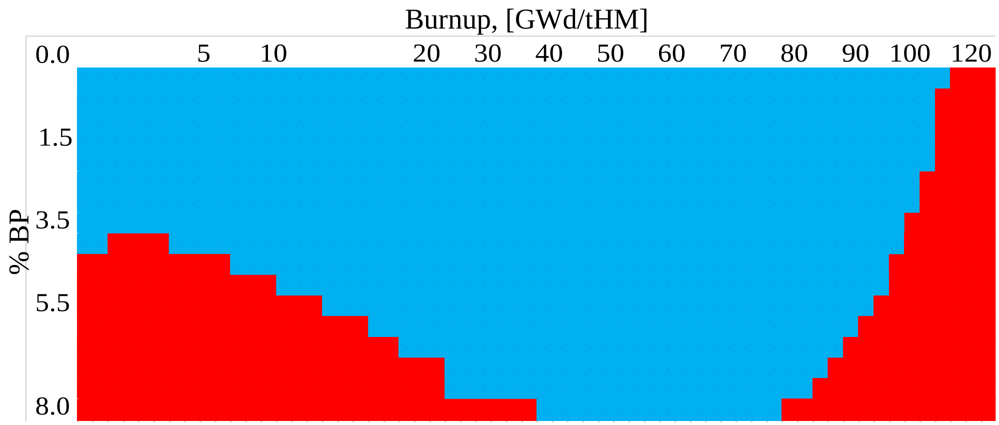

Fig. 4. Design space of fuel cell loaded 15 % U-235 enrichment fuel with BP

Following the logic of the previous section, initial reactivity excess is expected to be suppressed by adding erbium burnable poison. In this study, the BP is assumed to be homogeneously mixed to the UO_2 fuel. In order to minimize the percentage of BP addition in fuel pellet, the fuel of 15 % wt. U-235 enrichment is selected for further analyses. As shown in Table II, for the fuel of 15 % wt. U-235 enrichment, the required P/D varies from 1.25 to 1.85 meanwhile the equilibrium P/D of fuel with alternating cladding material, SiC, is 1.27. As mentioned in the previous section, the main idea behind the present paper is to use LEU as a once-through burning and no expanding beyond the present day fuel cycle technology that the fuel is burnt up to 100 GWd/tHM. Therefore, the P/D = 1.27 is preferably chosen option in following investigations.

For the identified fuel cell (that of 15 % wt. U-235 enrichment, and P/D = 1.27), Fig. 4 sketches the design space of fuel cell loaded 15 % U-235 enrichment fuel with BP addition. The possible designs that fulfill all criteria including reactivity safety parameters, moderator temperature coefficient, void coefficients, and Doppler coefficient along fuel cycle are colored in blue. Figure 5 shows k-inf evolution as a function of burning time for the some cases examined. It is found that, with the fuel of ≤ 1.0 % BP addition, even though the fuel cells are fulfilled all safety criteria, the k-inf values at some beginning burnup stages are higher than that of the reference fuel cell, k-inf being equal to 1.3950 as seen in Table II. For the fuel of ≥ 3.5 % BP addition, it is not preferable for designing because of positive feedback reactivity coefficients as shown in

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Fig. 2. Thus, the fuel of 1.0 to 3.5 % BP addition is preferable option since it gives a prominent benefit in terms of reactivity and safety parameters. Figure 6 presents the BOC neutron spectrum of some outstanding studied fuel cells. It is clear to see that the neutron spectra of the preferable design fuel cells are all harder than that of the reference fuel cells. The higher percentage of BP addition in fuel pellet is, the harder neutron spectrum of the fuel cell is, as shown in Fig. 6. This is because of the BP material strongly absorbs thermal neutrons [6], [7], [8], [9], [10], as in Table III.

Table III. Capture cross-section of Erbium

Isotope	Abundance, %	Thermal capture cross-section, barns	Resonance capture integral, barns
^{162}Er	0.1	29.18	574.83
^{164}Er	1.6	13.25	144.71
^{166}Er	33.6	20.81	110
^{167}Er	23	654.8	3906.6
^{168}Er	26.8	2.78	40.56
^{170}Er	14.9	5.91	58.57

V. CONCLUSIONS

This paper presents the neutronic analysis of fuel design for a long-life core in a pressurized water reactor with uranium oxide fuel and burnable poison of erbium. It is found that use of the fuel of 15 % wt. U-235 enrichment and 1.0 to 3.5 % of Erbium as burnable poison makes it possible to design a PWR fuel that achieves high burnup, up to 100 GWd/tHM, without expanding beyond the present day fuel cycle technology and no compromising the main safety characteristics. In addition, using SiC as cladding material would enhance strength and ductility ATF cladding mitigate against severe accidents.

In the future study, this preliminary study would be refined and extended including full-core coupled neutronic-thermal-hydraulic analysis, stability analysis, transients and accidents analysis, as well as economic analysis. Furthermore, how to make use of the once-through burning fuel for energy production with employing fuel reprocessing would be considered in further study.

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