PRELIMINARY STUDY OF PLATE FUEL CONCEPT BASED ON COATED PARTICLE FOR RESEARCH REACTOR

HIDAYATULLAH RULLY and YONGHEE KIM
Korea Advanced Institute of Science and Technology
291, Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea

Corresponding Author : yongheekim@kaist.ac.kr

ABSTRACT

This paper presents a novel fuel concept based on a coated-particle-fuel (CPF) for a high-performance and ultra-safe research reactor design. Unlike the conventional U_3Si_2-dispersed fuel plate, small CPFs are randomly embedded in the Al matrix. A CPF is composed of two components: a central fuel kernel and a thin buffer layer. To optimize the U loading, several types of fuel such as UO_2 and UC are studied to achieve comparable U densities to U_3Si_2 or UMo based fuel. A 20 MWth pool type research reactor is considered to investigate the potential and characteristics of the new fuel concept. Neutronic analysis was performed by using the continuous energy Monte Carlo code Serpent. In this preliminary study, it is found that by using CPF, the fuel Doppler effect can be considerably enhanced, thus increasing the inherent safety of research reactors. A very high thermal neutron flux can also be achieved with the newly-proposed CPF-based fuel concept. Optimization of the fuel batching is currently being studied to obtain good power distribution and a higher achievable burnup. It can be safely concluded that the CPF-based plate fuel concept will provide a new way to design an ultra-safe and high-performance research reactor.

1. Introduction

Research reactors are mainly used to produce neutrons and carry out related experiments. The flux and spectrum of these neutron sources and availability of irradiation facilities determine the types of applications, and therefore the competitiveness of a research reactor. Nowadays, research reactors need to be considered not only as a tool to perform research activities, but also as assets that satisfy industry irradiation needs. Research reactors are designed to have competitive service parameters and to support a broad spectrum of studies in nuclear physics, solid-state physics, radiation material science, neutron activation analysis, neutron radiography of various products, silicon doping, and the production of medical and industrial isotopes. Research reactors can also be used as training facilities [1]. In this regard, high neutron flux is one important parameter that needs to be satisfied in the research reactor design.

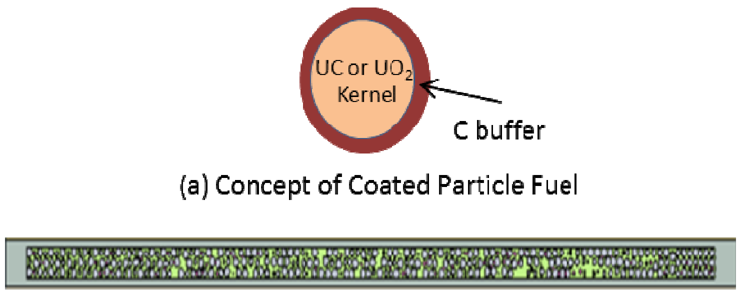
In addition to good performance, safety is also a design consideration for research reactors. For passive decay heat removal and shielding, research reactors are usually submerged in a large water pool. The pool reactor has been reasonably selected given its long history of safe and effective operation. To ensure the safety of the reactor, the fuel temperature coefficient (FTC) and coolant temperature coefficient (CTC) should both be negative. The combined effect of the fuel and coolant coefficients is the power coefficient of reactivity (PCR).

In the past, research reactors were normally fuelled with High Enriched Uranium (HEU). However, due to proliferation concerns, it is has become a priority to convert the HEU to Low Enrich Uranium (LEU) fuel. In the 1980s, the US initiated the program called RERTR[2] (Reduced Enrichment of Research and Test Reactor) to overcome the issue. One of its purposes is to develop new LEU fuel types with high uranium densities. Currently, the two most promising fuels are U_3Si_2 and UMo types due to their high uranium density which can reach up to ~4.8 g/cm^3 and ~8 g/cm^3.

In this work, we have tried to devise a new fuel concept to enhance generic reactor safety without compromising the reactor and fuel performances. As a new fuel concept, we propose a plate fuel concept based on a novel coated particle fuel (CPF) with several objectives: to improve the reactivity feedback of plate-type fuel, to obtain a very high neutron flux, to achieve a high burnup, and to develop a new LEU fuel with high uranium density. In Section 2, the concept of the new fuel concept is described. To investigate the neutronic feasibility of the new fuel concept, a model research reactor is considered. The neutronic calculations are performed using the Monte Carlo code Serpent [3].

2. Fuel Concept

Taking into account the goals of the new plate fuel concept, we came up with a plate fuel containing coated particle fuels (CPF). The basic concepts of the new plate fuel are depicted in Figure 1. As shown in Figure 1, CPFs are randomly dispersed in the Al matrix. For CPF, a fuel kernel is coated with a thin carbon buffer layer. The role of the porous buffer layer is to accommodate the fuel swelling due to burnup. The buffer thickness can be determined by taking into account to the swelling phenomena of the fuel [4,5]. Another consideration of plate type fuels is the fission gas release from the kernel. Taking into account the Al melting temperature (~660^{o}C), the maximum allowable temperature will be between 400 and 500^{o}C, ensuring that the fission gas release can be prevented in the new fuel design [6].



(a) Concept of Coated Particle Fuel

(b) Cross section of fuel plate

Fig 1. Schematic concept of the proposed plate fuel based on CPF

The fuel kernel can be either UC or UO_2. In this study, both type of fuels are considered. UO_2 fuel is finally adopted due to the well-known performance in a high temperature environment and achievable burnup. The UC fuel, on the other hand, has a higher density that can increase the U loading per plate, increasing the fuel inventory of the reactor. The size of the kernel needs to be optimized to achieve a high U loading. Table 1 shows the predicted U density comparison between UO2 and UC as a function of the kernel diameter. Additionally, a higher U density can be achieved by adopting a thicker fuel meat and larger fuel assembly that will lead to a noticeably higher fuel fraction in the core.

Kernel diameter/Buffer thickness	U Density (g/cm3)		Fuel Type	U Density (g/cm3)
	UO_2	UC		
650μm / 30 μm	3.51	4.74	U_3Si_2	4.8
700μm / 30 μm	4.46	6.02	UMo	8

Tab 1: Uranium density comparison.

3. Preliminary Conceptual Research Reactor Core Design

A 20 MWth pool-type reactor is considered to investigate the neutronic potential of the new fuel concept. Figure 2 shows the fuel assembly configuration, which is a box type assembly design. Design parameters of the fuel assembly are summarized in Table 2.

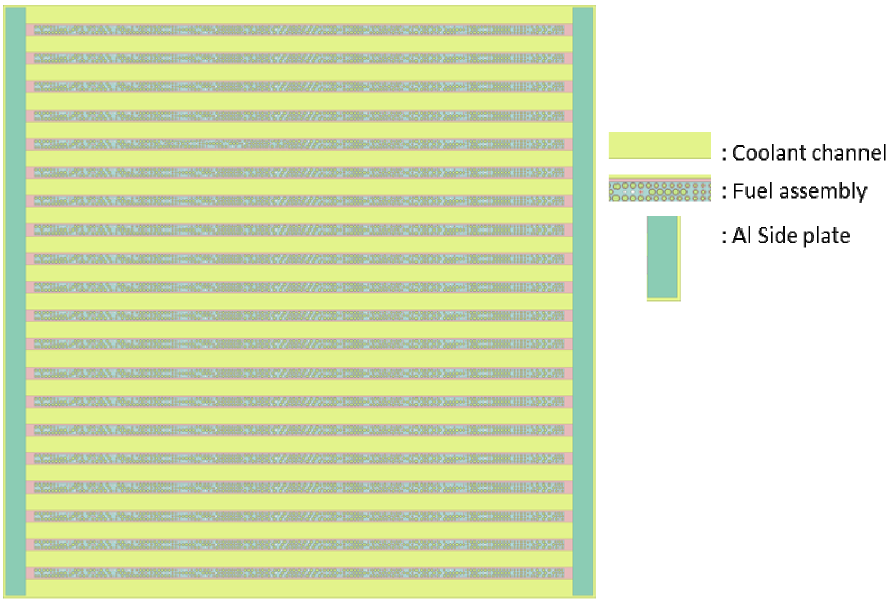


Fig 2. Fuel assembly configuration.

Parameter	Value
FA size (cm)	13 x 13
Coolant volume fraction (%)	54.6
Fuel plates volume fraction (%)	38.4
Side plates volume fraction (%)	7
Fuel meat thickness (mm)	2
Volume fraction of fuel meat (%)	28
Fuel volume fraction in meat/packing fraction (%)	50
Cladding thickness (mm)	0.34
Active fuel height (cm)	60
Side plate thickness (mm)	4.55
Number of fuel plates per assembly	20

Tab 2: Fuel Assembly design parameter

In this design, the fuel meat is much thicker (2mm) compared to the conventional fuel plate (~0.6mm). Thicker fuel plates and bigger fuel assembly size can also lead to the enhancement of mechanical integrity in terms of the critical coolant velocity [7].

For our scoping analysis, the kernel diameter is set to 650 μm and the buffer thickness is set to 30 μm. The fuel enrichment is 19.75% (LEU).

Figure 3 depicts the radial configuration of the proposed research reactor core design. The power density is set to 242.79 W/cc. The core is comprised of 8 fuel assemblies, reflectors, and irradiation holes. The reflector is a 13.8 cm x 13.8 cm beryllium box. One large irradiation hole is located at the core center and 12 others are located in the reflector region. In order to provide adequate control rods, Hf control rods are located in the inner core region. Another reason to put the control assembly in the inner region is to prevent a flux perturbation in the irradiation hole in reflector region.

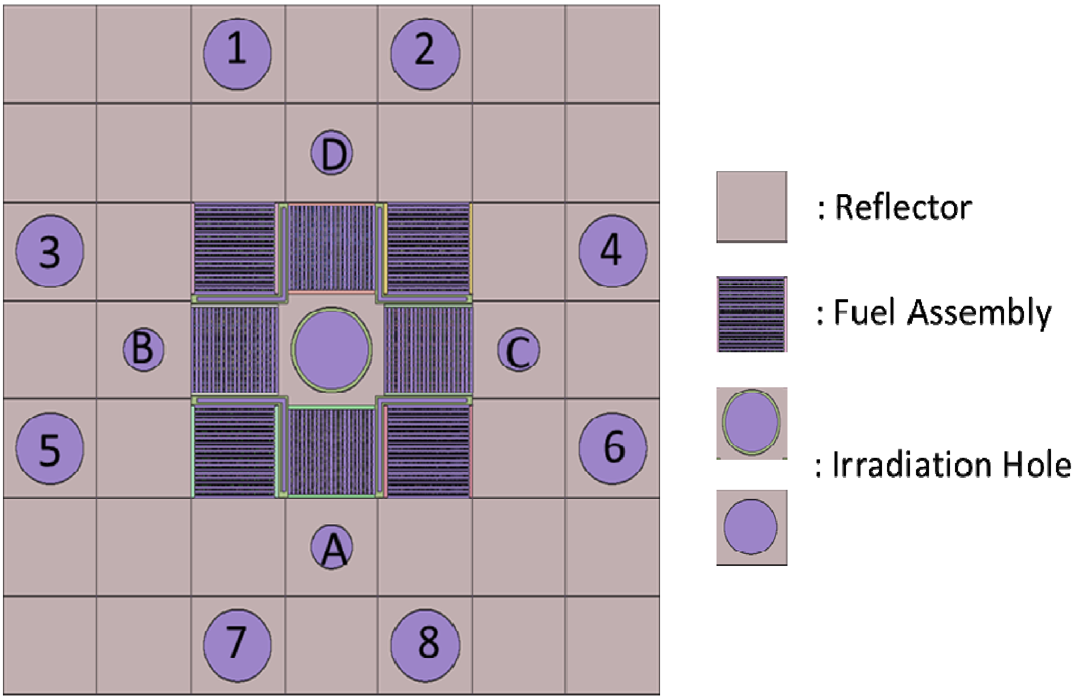


Fig 3. Radial core configuration of the research reactor

4. Result and Discussion

4.1. Preliminary Thermal analysis

The thermal analysis was mainly performed to investigate the core material temperature. For the thermal analysis, the axial power core distribution should be first determined. Figure 4 shows the axial power distribution of the core generated by Serpent. The axial power distribution from Serpent is one of the inputs for the MATRA_P codes [8] which calculates the fuel, cladding, and coolant temperature distributions along the axial direction in the core. Figure 5 shows the axial temperature profile along the average coolant channel for both types of fuel: UO_2 and UC. The calculation conditions are summarized in table 3.

In the CPF based fuel, a single fuel meat is highly heterogeneous, consisting of UO_2/UC fuel kernel, C buffer and an Al matrix which made it difficult to do the thermal analysis. In this preliminary study, to do the thermal analysis, the thermal conductivity is determined by using volume-average thermal conductivity [9],

$$\bar{k} = \frac{\Sigma V_i k_i}{V} \tag{1}$$

where : $\bar{k}$ = average thermal conductivuty

i = material index (UO2, UC, buffer and Al)

V = material volume

The thermal conductivity of each component is therefore temperature-dependent, which are modeled as follows: [10]

$$k_{UO2} = \frac{1}{0.0452 + 2.46x10^{-4}T + 0.00187b.u + (1 - 0.09\exp(-0.04b.u)x(0.00187b.u)\left(\frac{1}{1+396\exp\left(\frac{6930}{T}\right)}\right) + \frac{3.5x10^{9}\exp\left(\frac{16361}{T}\right)}{T^2}} \tag{2}$$

$$k_{UC} = 21.7 - 3.04x10^{-3}T + 3.61x10^{-6}T^3$$

$$k_{buffer(C)} = 78.294 - 8.603x\log(T)$$

$$k_{matri(Al)} = 95.17 + 0.22T^2 - 0.0004T^3 + 0.0000002T^3$$

where : b.u = burnup (GWd/MTU) ; T = Temperature (K)

Reactor power, MWth	20
Coolant inlet temperature, °C	40
Coolant density, g/cm^3	0.9923
Coolant pressure, Bar	1.8
Materials for coated fuel	UO_2/UC /C buffer/ Al
Density, g/cm^3	10.4/12.985/1.05//2.7
Average Coolant/cladding/fuel temperature (UO2),°C	44.9/81.0/83.9
Average Coolant/cladding/fuel temperature (UC),°C	46.6/82.1/84.9

Tab 3: Calculation condition for thermal analysis

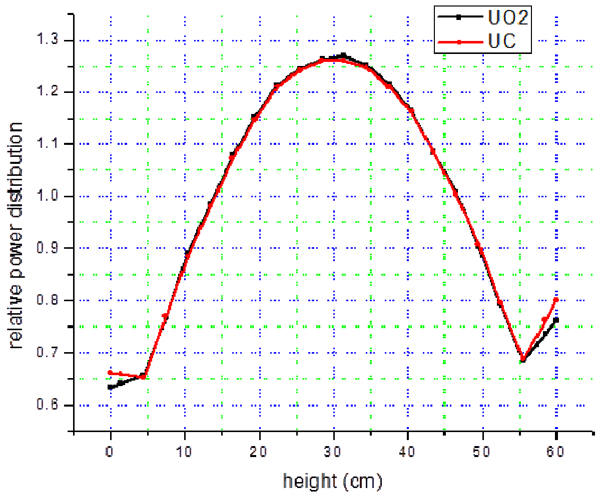


Fig 4 . Axial power profile of the research reactor

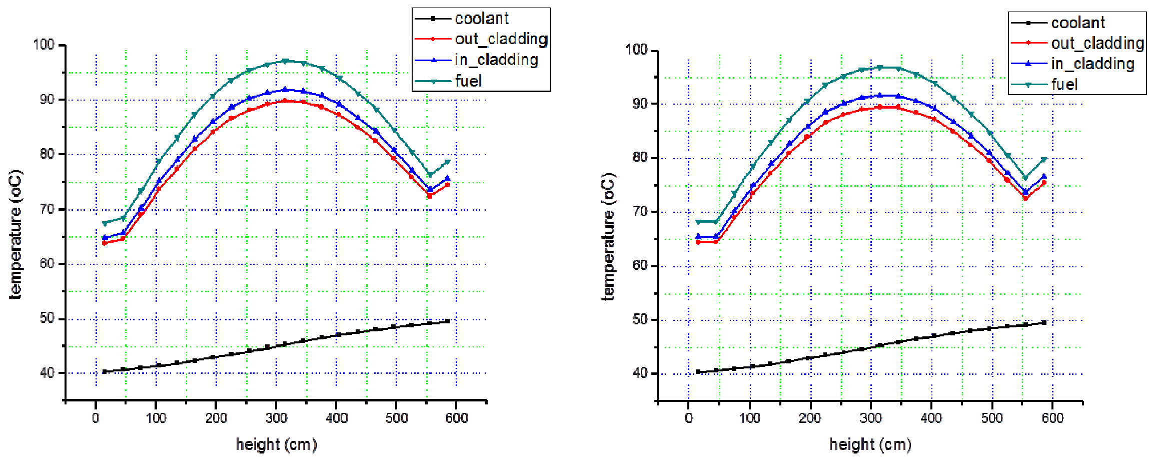


Fig 5 . Axial core temperature profile (UO_2 : left , UC :right)

It can be deduced from Figure 5 that the peak fuel temperature is about 100^{o}C for both fuel types. The cladding temperature is relatively high since the flow area is rather small due to the thicker fuel plate. With these high fuel temperatures, it is expected that the Doppler feedback will be improved in this design.

4.2. Equilibrium core searching

To gauge the performance in the equilibrium core condition, actual eight-batch fuel shuffling was simulated for both UO_2 and UC cases. The eight-batch fuel shuffling scheme is depicted in Figure 6. The cycle length is estimated to be 76 days for UO_2 fuel, and longer i.e 108 days for UC fuel. In the repetitive simulation, 5-days cooling down is also considered. The achievable burnup for each case are 153.82 MWd/kgU and 162.12 MWd/kgU respectively.

Figure 8 shows the actual evolution the k-eff value of the core. The pseudo-equilibrium cycle was obtained after the 8th cycle due to the 8-batch fuel management scheme. Figure 7 shows the radial power profile in the equilibrium core condition. The power peaking factor, about 1.3, occurred at the fresh fuel position, while the lowest power occurred at the 7th burned fuel position.

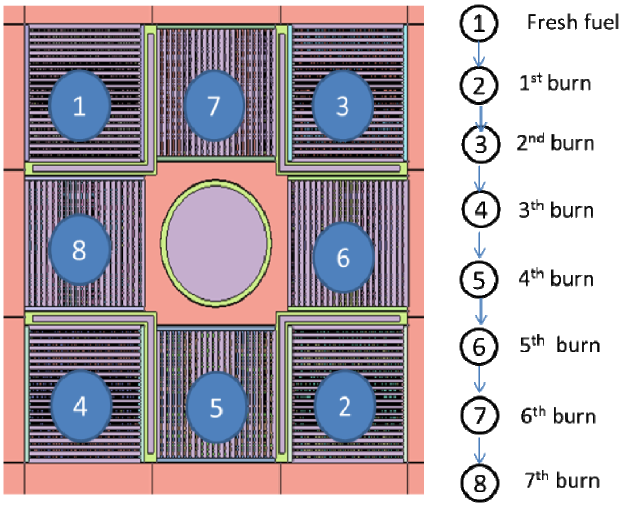


Fig 6 . 8 batch fuel shuffling scheme

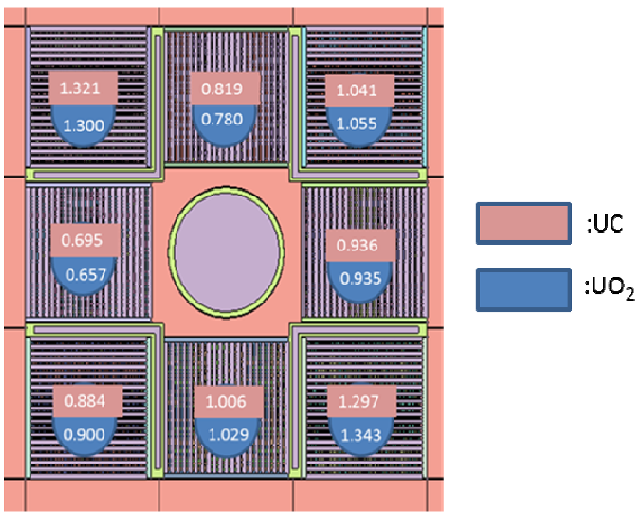


Fig 7 . Radial core power profile in equilibrium core condition

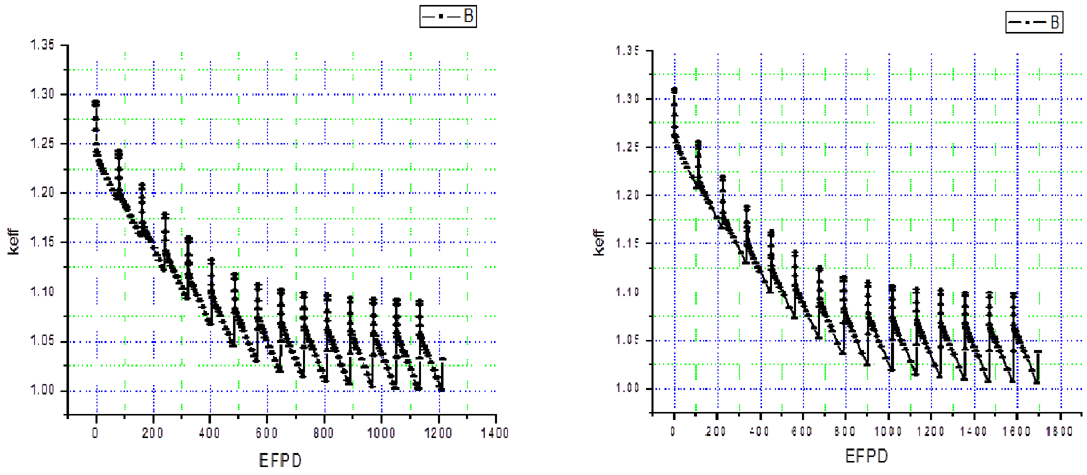


Fig 8 . Equilibrium core searching for fuel based on UC (left) and UO_2 (right)

4.3. Power Defect

High fuel temperature can lead to the enhancement of fuel Doppler effect, thereby enhancing inherent reactor safety. With the result of the previous thermal analysis, the power defect in the equilibrium core condition was performed. In this study, the power defect was decomposed into two main components: contribution from the coolant and fuel. The hot zero power and hot full power condition for calculation are summarized in Table 4 while the corresponding computed results are summarized in Table 5. As shown in table 5, the reactivity change due to coolant and fuel provides negative reactivity feedback at 100% power change. Therefore, the net power defect is clearly negative due to the enhancement of the Doppler effect. As such, it can be considered that the new design can provide enhancement of reactor safety.

	HZP condition	HFP Condition	
		UO_2	UC
Coolant Temperature (oC)	40	44.96	46.59
Coolant Pressure (bar)	1.8		
Coolant Density (g/cm^3)	0.9923	0.99035	0.9896
Fuel Temperature (^{o}C)	40	83.92	84.93

Tab 4: HFP and HZP Parameters for fuel defect calculation

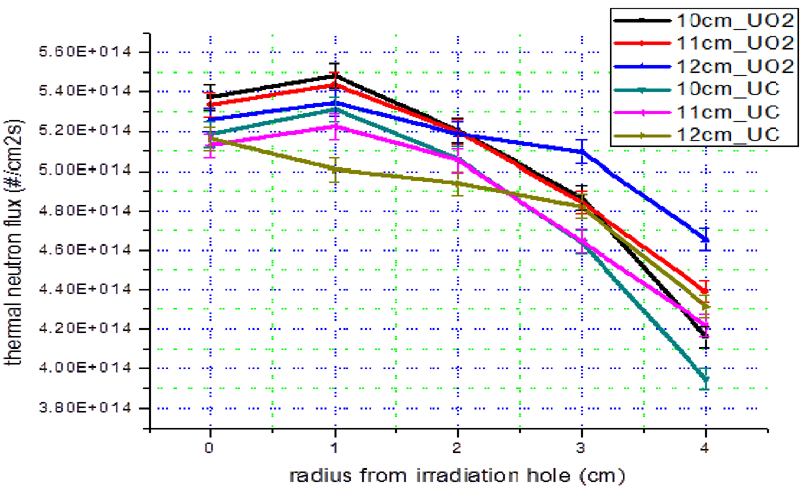
Power defect component	Reactivity (pcm)	
	UO_2	UC
Fuel temperature	-104.35 ± 2.23	-112.80 ± 2.04
Coolant temperature	-6.39 ± 2.33	-21.04 ± 1.98
Total	-110.74 ± 3.16	-133.85 ± 2.84

Tab 5: Components of power defect

4.4. Flux Calculation

Maximum neutron flux is an important parameter for modern research reactors. High neutron flux allows the succesfull operation of research and several applications, but greatly increase the complexity of the reactor design. The design is also expected to have irradiation facilities for thermal as well as fast energy spectrums. Fast neutron irrradiation is a promising technology for efficiency gain and life extension of the power superconductor [11].

Figure 9 shows the maximum thermal and fast neutron flux in the central irradiation hole as a function of the irradiation hole radius. In the UO_2 case, the maximum unperturbed thermal and fast neutron flux are 5.48x10^{14} n/cm^{2}s and 2.54x10^{14} n/cm^{2}s. Instead for the UC case, the values are 5.34x10^{14} n/cm^{2}s and 2.56x10^{14} n/cm^{2}s. Meanwhile Table 2 depicts the flux values at the irradiation holes located in the reflector region. From Figure 9 and Table 2, we can note that the high neutron fluxes, both thermal and fast, can be obtained using a simple box fuel assembly geometry.



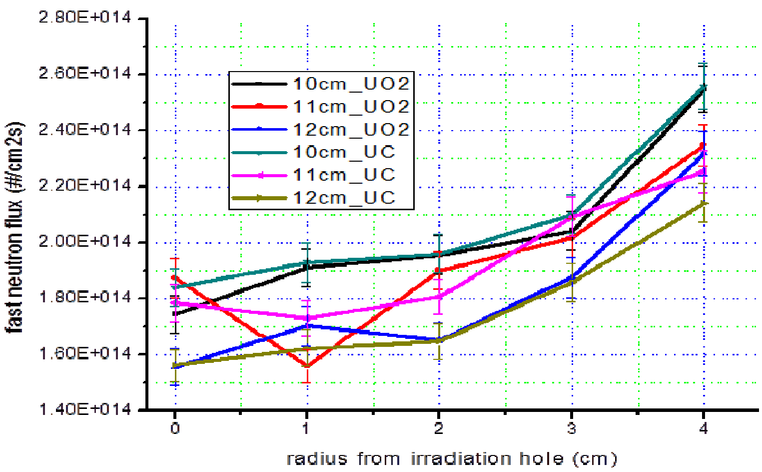


Fig 9 .Flux Profile in centre irradiation hole (thermal :up ; fast :bottom)

Position	Neutron Flux (n/cm^2s)			
	UO_2 Based		UC Based	
	Thermal	Fast	Thermal	Fast
1	8.40E+13 ± 1.09E+11	9.52E+12 ± 3.72E+10	8.19E+13 ± 1.06E+11	9.55E+12 ± 3.72E+10
2	7.65E+13 ± 1.04E+11	8.39E+12 ± 3.57E+10	7.36E+13 ± 1.02E+11	8.29E+12 ± 3.61E+10
3	8.15E+13 ± 1.07E+11	9.22E+12 ± 3.67E+10	7.93E+13 ± 1.04E+11	9.23E+12 ± 3.69E+10
4	7.98E+13 ± 1.06E+11	8.70E+12 ± 3.65E+10	7.67E+13 ± 1.05E+11	8.61E+12 ± 3.56E+10
5	6.88E+13 ± 1.00E+11	7.33E+12 ± 3.34E+10	6.56E+13 ± 9.78E+10	7.16E+12 ± 3.30E+10
6	8.89E+13 ± 1.16E+11	1.01E+13 ± 3.93E+10	8.53E+13 ± 1.13E+11	9.94E+12 ± 3.91E+10
7	7.44E+13 ± 1.01E+11	1.01E+13 ± 3.51E+10	7.08E+13 ± 1.01E+11	7.88E+12 ± 3.44E+10
8	8.82E+13 ± 1.12E+11	9.85E+12 ± 3.92E+10	8.49E+13 ± 1.11E+11	9.85E+12 ± 3.79E+10
A	3.01E+14 ± 3.13E+11	1.23E+14 ± 2.22E+11	2.84E+14 ± 3.01E+11	1.21E+14 ± 2.19E+11
B	2.60E+14 ± 2.89E+11	1.00E+14 ± 2.01E+11	2.47E+14 ± 2.79E+11	9.92E+13 ± 1.99E+11
C	3.00E+14 ± 3.09E+11	1.21E+14 ± 2.22E+11	2.85E+14 ± 3.08E+11	1.19E+14 ± 2.18E+11
D	2.87E+14 ± 2.95E+11	1.13E+14 ± 2.15E+11	2.74E+14 ± 2.96E+11	1.12E+14 ± 2.09E+11

Tab 6: Neutron flux at irradiation hole located in reflector region

5. Summary

A new plate fuel concept based on a coated particle fuel is proposed to improve negative reactivity feedback from fuel and coolant temperature. A coated UO_2 or UC fuel kernel with a thicker fuel meat and a larger fuel assembly is adopted in this design to increases the fuel volume fraction in the whole core. With the well-verified UO_2 kernel, the effective fuel loading in a core is expected to be comparable to that of the current U_3Si_2 fuel. If a UC kernel is used, a much higher fuel loading can be achieved due to its significantly higher density. Furthermore, its performance is rather similar to that of the UO_2 kernel. The neutronic feasibility has been demonstrated by considering a small 20 MWth research reactor. It has been shown that the Doppler feedback can be greatly enhanced with the new fuel concept and a very high thermal flux can be achieved by using a simple box-type fuel assembly design. It is concluded that the newly proposed fuel concept deserves more detailed R&D efforts and has considerable potential as a high-performance and ultra-safe research reactor fuel.

REFERENCE

[1] I.T. TRETIYAAKOV, et al., “Project Development for Promising Pool-Type Research Reactor” Trans. Intl Mtg on RRFM, St.Petersburgh. The Russian Federation, 2013, European Nuclear Society (2013)

[2] http://www.rertr.anl.gov/

[3] L. JAAKKO, “PSG2 / Serpent – a Continuous-energy Monte Carlo Reactor Physics Burnup Calculation Code,” VTT Technical Research Centre of Finland (2012)

[4] HIDAYATULLAH,R. ,KIM YH, “Feasibility of Coated Particle Fuel for a High-Performance, Ultra-safe Research Reactor,” Trans. Intl Mtg on RRFM, St.Petersburgh. The Russian Federation, 2013, European Nuclear Society (2013)

[5] HIDAYATULLAH,R. ,KIM YH, “A New Coated UO2 Particle Fuel for Ultra-high Performance Research Reactor,” Trans. American Nuclear Society Meeting, Atlanta. United States, 2013, American Nuclear Society (2013)

[6] D. J., SENOR et al., “A New Innovative Spherical Cermet Nuclear Fuel Element to Achieve an Ultra-Long Core Life for use in Grid-Appropriate LWR’s,” PNNL-16647, Pacific Northwest National Laboratory (2007)

[7] HIDAYATULLAH,R. ,KIM YH, “A Novel Plate Type Fuel Concept Based on Coated Particle for Research Reactor,” Trans. Korean Nuclear Society Spring Meeting, Gwangju, Rep of Korea, 2013, Korean Nuclear Society (2013)

[8] Core Thermal_Hydraulics Design Group, “Input Instruction of MATRA_P”, 2013, KAERI, Republic of Korea (2013)

[9] J.K. CARSON et al., “Thermal Conductivity Bounds for Isotropic Porous Materials”, Int.J. Heat Mass Transfer (2005)

[10] K. GEELGOOD, et.al, “Feasibility assessment of using TRISO Particles in AFPR,” PNNL-16225, Pacific Northwest National Laboratory (2007)

[11] H.C KIM, et al., “Preliminary Neutronic Design for Fast Neutron Irradiation Facility in the KIJANG Research Reactor,” Trans. Korean Nuclear Society Spring Meeting, Gwangju, Rep of Korea, 2013, Korean Nuclear Society (2013)