NEUTRONIC DESIGN OF THE RPI REACTOR CORE USING HIGH DENSITY OF U_3SI_2/AL FUEL

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Abstract *The research reactor being designed is called the radioisotope production reactor (RPI). The RPI is used for radioisotope production so that it can keep up with the development in radioisotope needs from both the nuclear and health industries. This reactor can operate with U_3Si_2Al plate-type fuel with a density of 4.80 grams/cc. In this research, neutronic calculations have been carried out for the design of the RPI core using MTR type U_3Si_2/Al fuel with power 2, 5, and 10 MW. This activity begins by generating macroscopic cross-sections for core fuel as a function of temperature and fuel burnup. Cross-section generation was carried out with the WIMSD-5B code using the ENDFB-VIII.0 library. Calculation of the neutronic parameters was carried out using the Batan-FUEL code. Based on the results of calculations for a core configuration of 14 fuel elements and 4 control elements on a 5 x 5 grid, this reactor core meets safety limits by using U_3Si_2/Al fuel. The average thermal neutron flux at the center of the core is 1.09×10^{14} n/cm^{2}s and the cycle length is 250 days at 5 MW power. The calculation results show that the RPI core meets the neutronic safety criteria on high-density fuel*

INTRODUCTION

Indonesia has 3 research reactors, namely the RSG-GAS reactor in Serpong, the TRIGA 2000 reactor in Bandung, and the Kartini reactor in Yogyakarta, but all of them are old. The RSG-GAS is still operating, but the TRIGA has a problem with the bubble when operated, the Kartini reactor was already shut down. These research reactors have been used for radioisotope production, education, and research activities or material testing. Therefore, research reactors in Indonesia have made a major contribution to the development of industry, energy, health, and especially radioisotope production(1)(2)(3). Therefore, it is planned to design a new research reactor specifically only for the production of radioisotopes so that its name is called the Radioisotope Production Reactor (RPI), but its power is still varied from 2, 5, and 10 MW. This new research reactor uses plate-type silicide fuel which has the same dimensions as the RSG-GAS reactor fuel. So far, RSG-GAS reactor fuel has had experience using plate-type fuel produced domestically by PT INUKI. The fuel used in this new research reactor is U_3Si_2/Al with high density (4)(5)(6).

The main objective of this research is to neutronically design the RPI core with a silicide plate-type fuel density of 4.8 grams/cc with various powers. The benefit of using U_3Si_2-Al with high density is that it is available in the world and has been used in other research reactors in the world. The results of this core design are expected to have a new research reactor design with a small core but high thermal neutron flux. The small core makes it easy to manage fuel in the core. This core design uses graphite as a reflector material. With various levels of power, it is hoped that the most optimal core configuration can be determined.

The core configuration that will be determined is a reactor core that can be operated with an equilibrium core (7)(8)(9). This work only determines the neutronic parameters of the core with high-density uranium silicide fuel.

The neutronic design of the core was carried out using the WIMSD-5B (10) and Batan-FUEL (11) codes, which have been extensively validated using experimental data of the RSG-GAS reactor (12)(13). Design parameters such as excess reactivity, shutdown margin, stuck rod condition, and power peak factors must meet the safety requirements of reactor operation. The design of the RPI core is expected to produce a high thermal neutron flux, and have a high level of safety. The neutron flux is also used to determine core power, power distribution in the core, and maximum discharged burnup fuel.

METHODOLOGY

A. Cross-Section calculation

The fuel element is made up of 21 fuel plates with the same thickness and width that are spaced out by the same amount on both sides by AlMgSi side plates. The coolant gap is 2.55 mm, which is the distance between two fuel plates. The dimensions of the control element's exterior cross-section match those of the fuel element. The absorber blade is put into two pairs of control guide plates, which replace the outer three plates on each side. The overall dimensions of the fuel plate are 1.30 mm x 625.5 mm x 70.75 mm for the 19 inner plates and 1.30 mm x 693.5 mm x 70.75 mm for the outside plates (14)(15)(16). The fuel consists of 19.75 weight percent U^{235} enrichment of uranium present in the meat. Table 1 displays the essential statistics for the control and fuel elements. Initial loads of 250 and 178.6 g U^{235} were placed into fuel elements with a composition of 21 fuel plates, as shown in Figure. 1 shows the core of RPI. Figure 2 shows the standard fuel element consisting of 21 plates. The standard control element has 15 fuel plates, as shown in Figure. 3, which serve as control elements.

The fuel plate is composed of fuel meat that is 0.54 mm thick and is covered in 0.388 mm $AlMg_2$ cladding. Dispersed in an aluminum matrix, U_3Si_2 powder serves as the fuel meat. The fuel meat's entire measurements are 0.54 x 600.0 x 62.75 mm (17)(18).

The RPI reactor consists of 14 fuel elements and 4 control elements shown in Figure 1. The type of fuel used is plate type. Nuclear fuel data can be seen in Table 1. Fuel in 2-dimensional form can be seen in Figure 2, modeled for WIMSD-5B input as in Figure 3. The control rod used is a fork-type using an AgInCd absorber with a percentage of 80%.15 % and 5 % for each material, respectively (19). The control rod in 2-dimensional form can be seen in Figure 4, modeled for WIMSD-5B input in Figure 5. Four control rods, each with 15 fuel plates, four standard FEs with a light water moderator, graphite reflector elements, and additional irradiation facilities are located on the five-by-five core grid places.

The cross-section for the library will be generated using MWSD-5B code from fuel elements and core material in the RPI reactor. WIMSD-5B input model will be modeled for fuel and control rod Code. The WIMSD-5B is a program package developed at the United Kingdom Atomic Energy Establishment for reactor physics calculations (20).

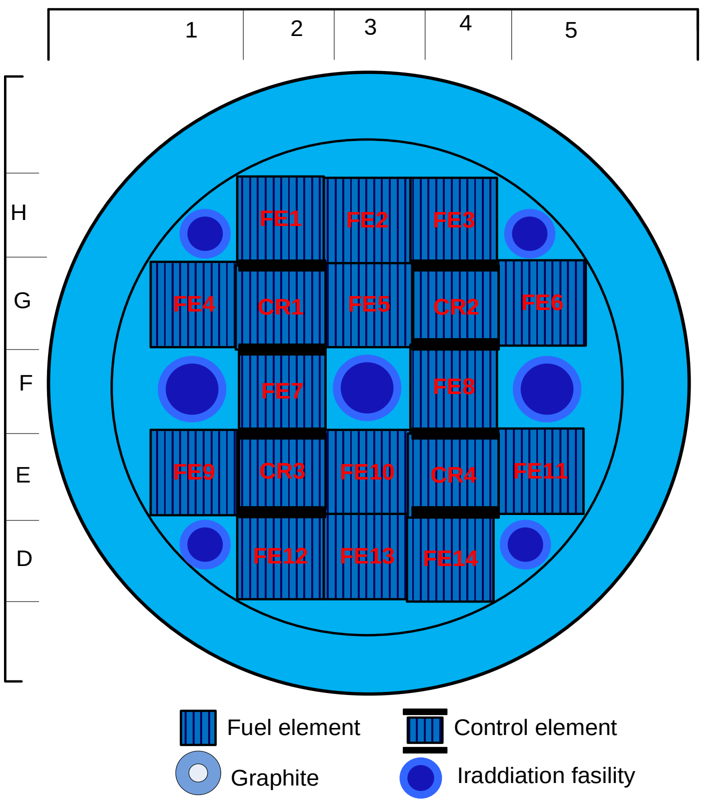

Figure 1. Core configuration with 14 fuel elements and 4 control elements (20)

Table 1. Nuclear parameter of silicide fuel of the RPI core (21)

Parameter	Values
Number of fuel elements in the core	14
Number of fuel plate elements	21
Number of control elements in the core	4
Number of fuel plates in the control element	15
Dimension of the standard fuel element and control element, mm	77.1 × 81 × 600
Thickness of fuel meat, mm	1.3
Cooling channel width, mm	2.55
Material of cladding	$AlMg_2$
Material of edge plate	$AlMg_2$
Thickness of cladding for fuel, mm	0.38
Dimension of the active zone, mm	0.54 × 62.75 × 600
Material of fuel	U_3Si_2-Al
Enrichment, %	19.75
Massa ^{235}U, g	400
Material of absorber	AgInCd
Thickness of absorber, mm	3.38
Material of absorber cladding	SS-321
Thickness of absorber cladding	0.85
Thickness of fuel meat, cm	0.054
Cladding thickness, cm	0.038
Cooling channel width n, cm	0.255
Dimension core grids, cm × cm	8.1 × 7.71

WIMSD-5B is used in lattice cell calculations which use transport theory to calculate flux as a function of power and position within the cell. In general, the WIMSD-5B program is divided into 3 blocks, namely multi-group calculation, main transport, and edit block. In the first part, calculate the neutron energy spectrum according to the choice of geometry and use it to condense the number of energy groups into fewer groups according to the input data. In the second part, the transport equations for a few groups are solved with a more detailed spatial model. In the editing section, several corrections are made to the results obtained previously. The WIMSD-B5 program library has 69 neutron energy groups with a power range of 0–10 MeV. The neutron energy spectrum used for each energy range in the column is divided into 4 groups (few groups), namely (22):

1. Fast neutrons, groups 1-5 with energy 0.831 MeV - 10 MeV
2. Deceleration neutrons, group 6-15 with energy 5.531 KeV - 0.831 MeV
3. Resonant neutrons, group 16-45 with energy 0.625 KeV - 5.531 KeV
4. Thermal neutrons, group 46-69 with energy <0.625 eV

WIMSD-5B output results are flux per unit volume and flux per mesh point, Diffusion coefficient (D), macroscopic fission cross-section, absorption, transport, nu-fission, and neutron spectrum result, and the scattering macroscopic cross-sectional matrix. The infinite multiplication factor and the macroscopic group constant, as a library can be used for core calculations.

B. Core Calculation

Core calculation of 2-D neutronic parameters using the Batan-FUEL program package using the transport method, where the transport equation parameters are fulfilled by the cross-section that has been generated by the WIMSD-5B program. The Batan-FUEL (23) program is to determine neutronic parameters such as k-eff value, cycle length, PPF, neutron flux distribution, and one stuck rod condition. In determining the core reactivity value, it is necessary to calculate (without control rods) first the conditions at "the beginning of the cycle" (BOC) (when the Xenon is in equilibrium and cold full power = CFP) and "end of the cycle"(EOC) (when the Xenon is in equilibrium and hot full power = HFP).

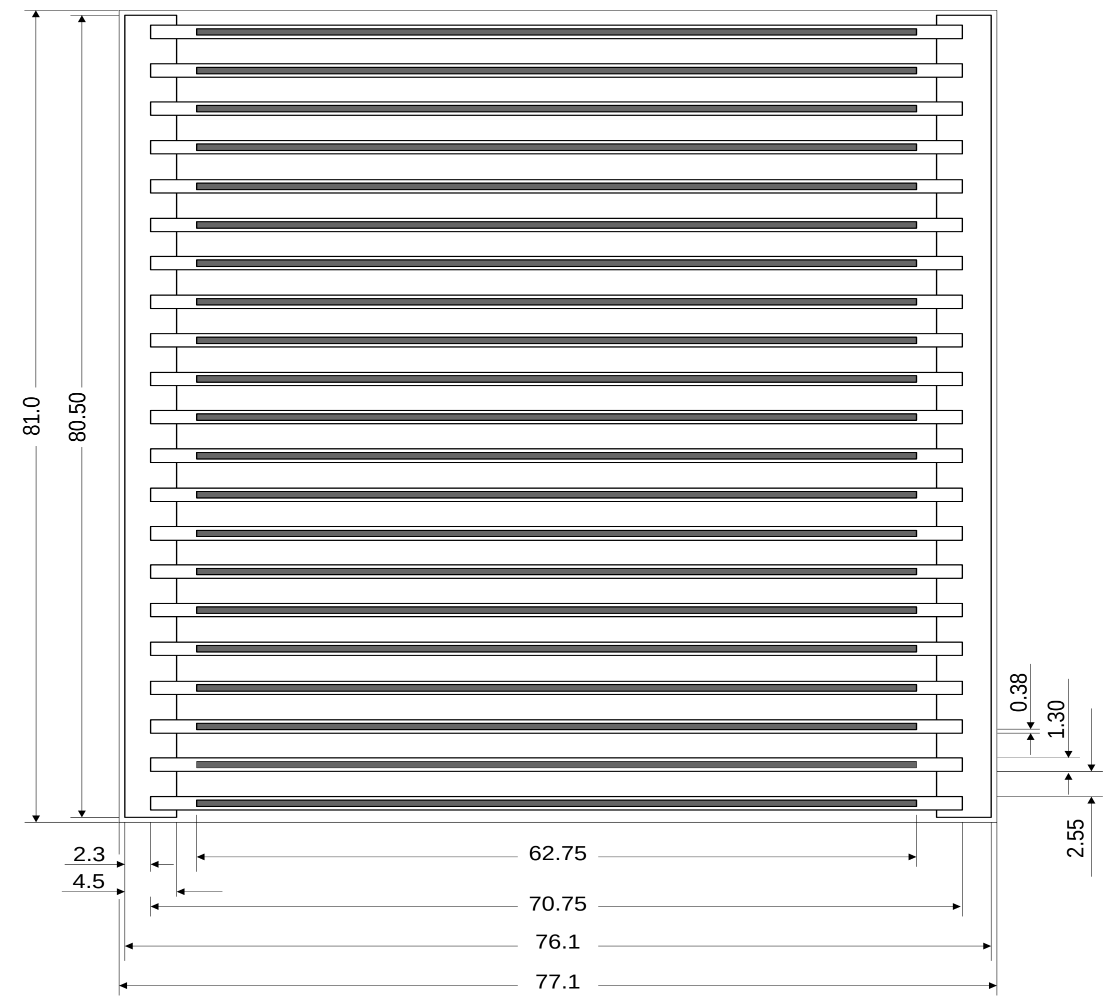

Figure 2. The standard fuel element of the RPI core (24)

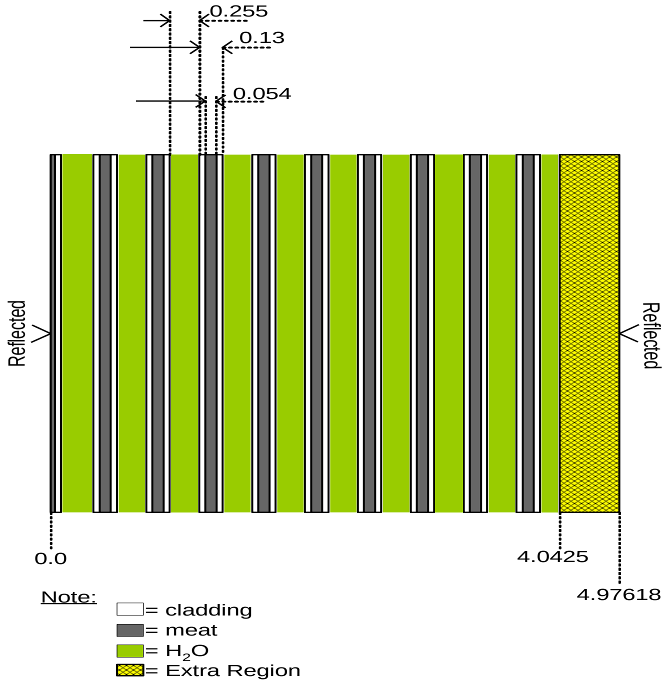

Figure. 3. Fuel element cell model (25)

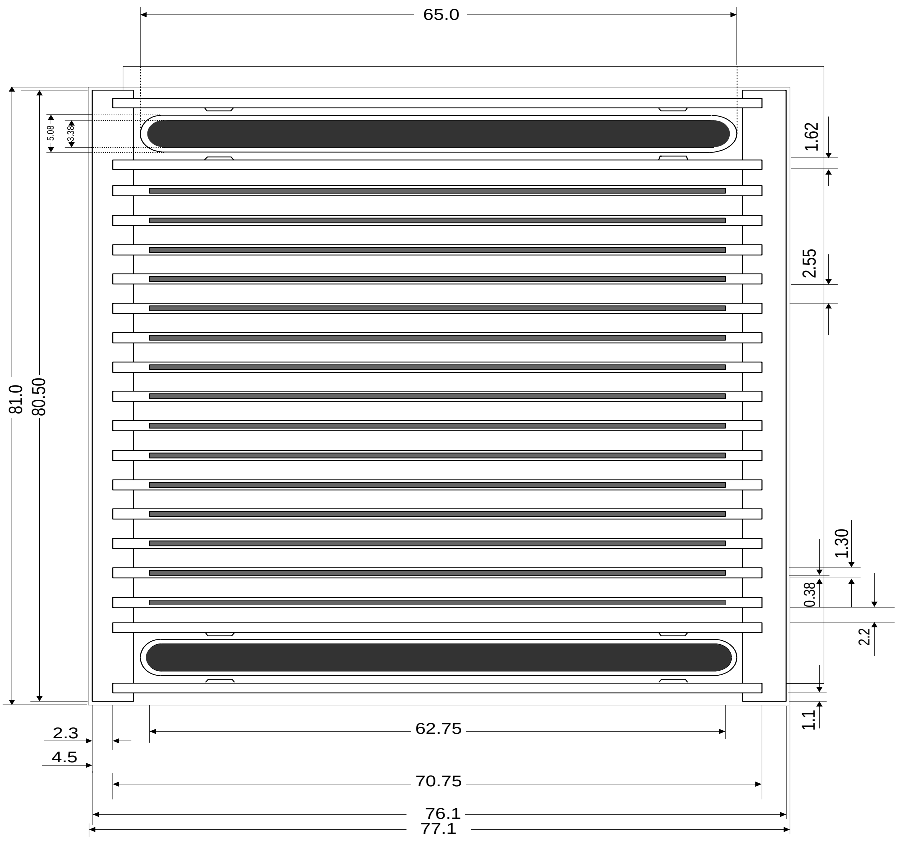

Figure 4. Control rod fuel element (26)

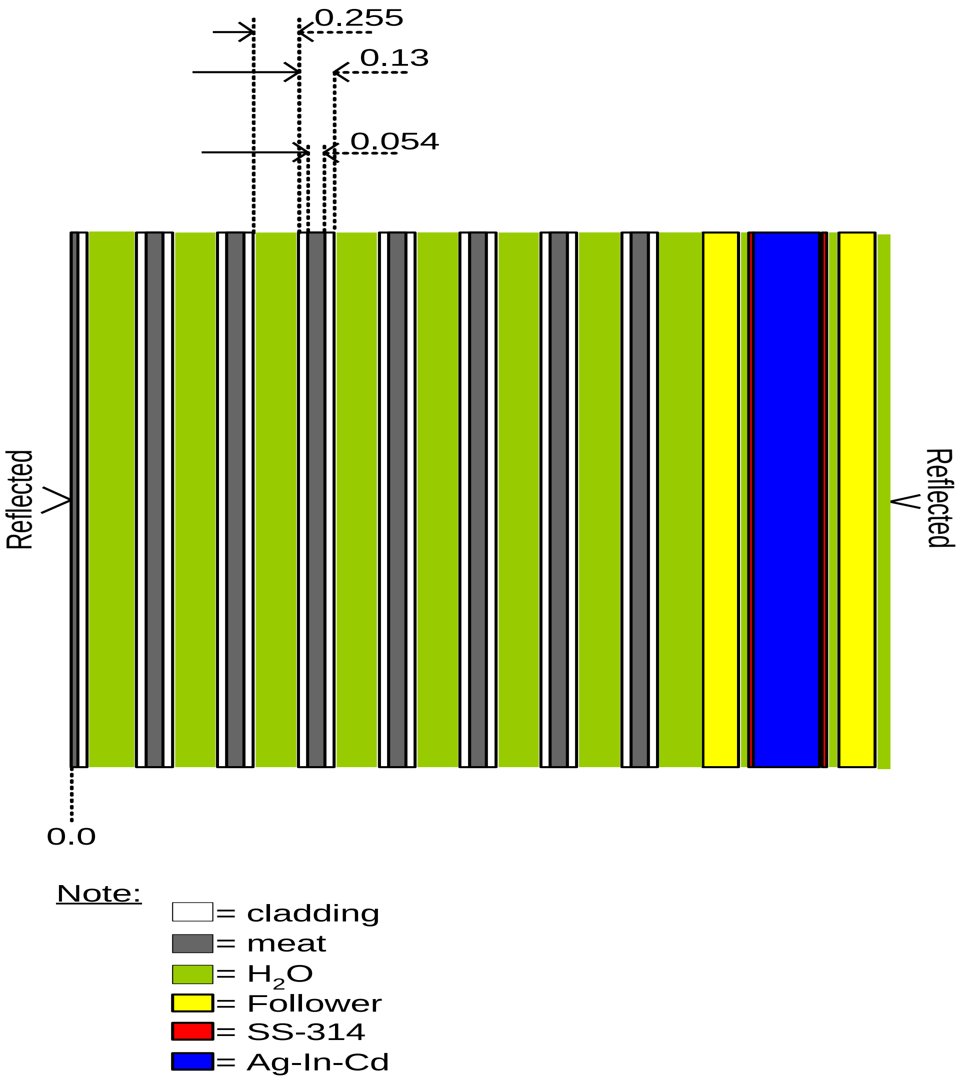

Figure 5. Ag-In-Cd absorber cell model (27)

RESULTS AND DISCUSSION

An equilibrium core was used in the core computation utilizing the Batan-FUEL code. Figure 6 shows the most optimal core arrangement with 4.8 g/cc density silicide fuel. The four burn-up classes created by dividing the 14 fuel and 4 control elements in the core into four groups could sustain the excess reactivity of the core at 1%, which would be sufficient for reactor operation at EOEC ("ending of the equilibrium core") condition. The values of the power peaking factor (PPF) are lower than 1.4 for "Beginning of the equilibrium core" (BOEC) and "End of the equilibrium core condition" (EOEC).

The equilibrium core's neutronic properties for power levels 2, 5, and 10 MW are compiled in Table 2. From Table 2, it is evident that for a single stuck-rod scenario, the safety restriction about subcriticality is consistently met.

The reactor's ability to be shut down under any operating situation is guaranteed by the shutdown margin's value. Table 2 shows that the overall excess reactivity for the equilibrium core inserted at 2, 5, and 10 MW is 11.20 %, 9.77%, and 9.23 %, respectively.

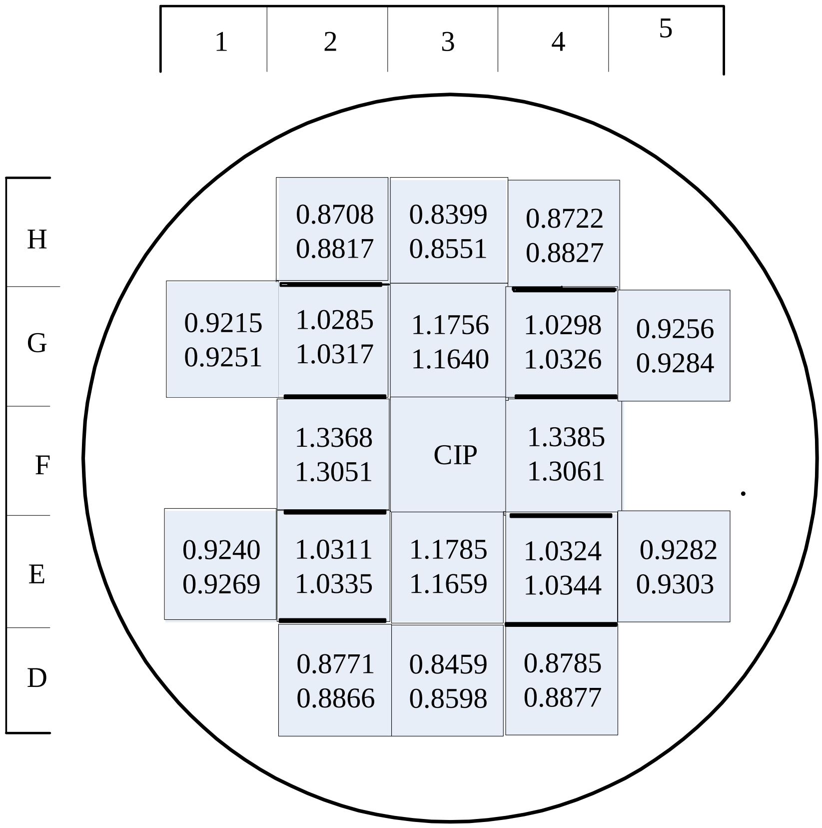

Figure 6. PPF values at BOC and EOC of the RPI core

Table 2. Calculation results of the neutronic parameter of the RPI core

Core parameter	RPI - Core 14/4 (14 fuel elements and 4 control elements)		
Power (MW_{th})	2	5	10
Massa ^{235}U per standard fuel element (g)	400	400	400
Uranium density (g/cm^3)	4.80	4.80	4.80
Cycle length (days)	550	250	145
Reactivity for one cycle (%Δk/k)	4.523	4.678	5.180
Reactivity xenon equilibrium (%Δk/k)	3.45	3.56	3.78
Excess reactivity (%Δk/k)	11.20	9.77	9.23
Total control rod values (%Δk/k)	-19.75	19.75	-19.75
Shutdown reactivity (stuck rod) (%Δk/k)	-8.55	-9.98	-10.25
Maximum Radial PPF	1.3358	1.3462	1.3584
Maximum discharged burn-up (%)	47.63	53.51	61.06

The equilibrium core's core cycle length was determined to be 550 days, 250 days, and 145 days under the fuel management technique for 2, 5, and 10 MW, respectively. The core cycle length provided by the RPI core design is very long. The equilibrium core's neutronic parameters at BOC condition are compiled in Table 2. The reactor's shut-down margin is the amount of negative reactivity in the control rods. To maintain conservative safety, control rods need to be sufficiently reactive to cause the reactor to shut down under all operating circumstances, even if the majority of reactive control rods are unable to enter the core. The equilibrium core is more cost-effective in this design because the core design uses a small equilibrium core that is more efficient than a core with single discharged fuel. The fuel that has been used can still be used again in the equilibrium core, just arrange the fuel in the core. So the equilibrium core's core parameters need to be calculated. Table 3 displays the average thermal neutron flux at the power level of 2, 5, and 10 MW. The average thermal flux is in the center position and the flux always has a strong correlation with power. The higher the power of the reactor, the thermal neutron flux also higher. These thermal fluxes in the irradiation positions are enough for radioisotope production especially the core design with a 10 MW power level. The RPI reactor core design meets the expected qualifications.

In Figure. 7, the computed radial neutron flux distribution is displayed. The highest thermal neutron flux value is observable in the core's central flux trap, and it decreases exponentially with increasing distance from the center. While the neutron moderation to thermal neutrons is causing a rapid decrease in neutron energy. The reflector reflects the neutron that exits the active core, causing the same effect to occur on the periphery of the core where the magnitude of the thermal neutron flux increases. Since fission-generated neutrons are significantly slowed down in both elastic and inelastic collisions with water, the fast neutron drop in the core is different from the thermal flux form.

The radial neutron flux distribution calculation's findings the highest neutron flux values calculated at the core center at 2 MW power were 6.37 x 10^{13} n/cm^{2}s for thermal neutrons, 1.458 x 10^{13} n/cm^{2}s for epithermal neutrons, and 1.257 x 10^{13} n/cm^{2}s for fast neutrons. The average thermal neutron flux for the RPI core is 4.340 x 10^{13} n/cm^{2}s; this thermal neutron flux is enough to irradiate the sample to produce a radioisotope in the RPI core.

Table 3. Average thermal neutron fluxes at the irradiation facilities. (n/cm^{2}s)

Irradiation positions	2 MW	5 MW	10 MW
CIP/F-3	4.34x10^{13}	1.09x10^{14}	2.21x10^{14}
H-1	2.19x10^{13}	0.55x10^{14}	1.12x10^{14}
H-5	2.19x10^{13}	0.55x10^{14}	1.11x10^{14}
F-1	2.59x10^{13}	0.65x10^{14}	1.32x10^{14}
F-5	2.55x10^{13}	0.64x10^{14}	1.29x10^{14}
D-1	2.19x10^{13}	0.55x10^{14}	1.11x10^{14}
D-5	2.63x10^{13}	0.66x10^{14}	1.34x10^{14}

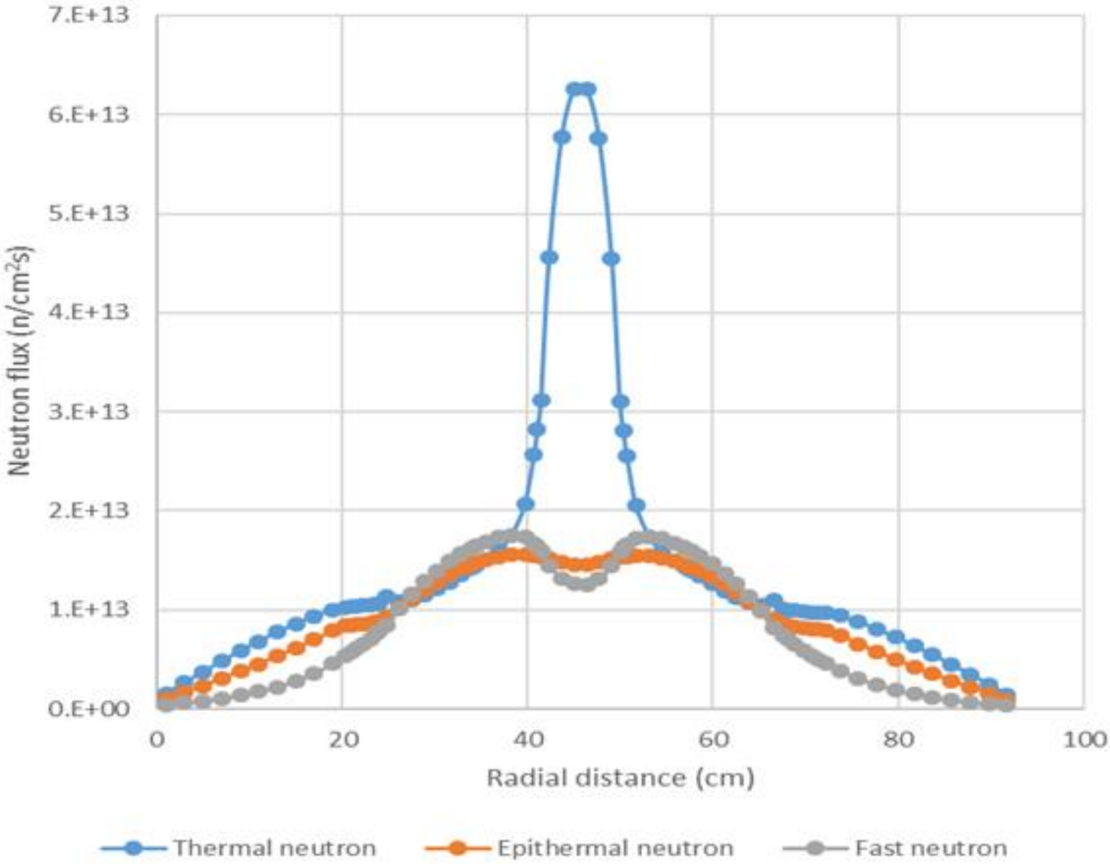

Figure 7. Distribution of neutron flux at the power of 2 MW

CONCLUSION

The results of the calculation of the neutronic parameters of the RPI core with a 5 x 5 grid and 14 fuel elements, 4 control elements, show that the power of 2, 5, and 10 MW meets the safety requirements from a neutronic parameter aspect. The parameters that differentiate them are the length of the operating cycle and the thermal neutron flux in the irradiation facility. The higher the power, the shorter the operating cycle length, namely 145 days, for 10 MW of power level, but the thermal neutron flux is in the order of 10^{14}, whereas for 2 MW power the cycle length is 550 days but the thermal neutron flux in the irradiation facility is in the order of 10^{13}. The design of the RPI core can be achieved as a thermal high flux at a small core using 18 fuels and fulfilling the safety criteria.

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