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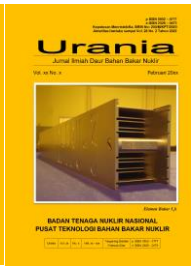

VALIDATION OF SRAC CODE SYSTEM FOR NEUTRONIC PARAMETERS CALCULATION OF THE PWR MOX/UO_2 CORE BENCHMARK

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ABSTRACT

VALIDATION OF SRAC CODE SYSTEM FOR NEUTRONIC PARAMETERS CALCULATION OF THE PWR MOX/UO_2 CORE BENCHMARK. Determination of neutronic parameter value is an important part in determining reactor safety, so accurate calculation results can be obtained. This study is focused on the validation of SRAC code system in the calculation of neutronic parameters value of a PWR (Pressurized Water Reactor) reactor core. MOX/UO_2 Core Benchmark was choosed because it is used by several researchers as a reference core for code validation in the determination of neutronic parameters of a reactor core. The neutronic parameters calculated include critical boron concentration, delayed neutron fraction and Power Peaking Factor (PPF), and its distribution in axial and radial directions. When compared with reference data, the calculation results of the critical boron concentration value show that there is a difference of 22.5 ppm on SRAC code system. Meanwhile, differences in power per fuel element (assembly power error) value of power-weighted error (PWE) and error-weighted error (EWE) is 2.93% and 3.94%, respectively. Maximum difference between PPF value in axial direction with reference reaches a value of 4.57%. SRAC calculation results also show consistency with the calculation results of other program packages or code. Results of this study indicate that SRAC code system is still quite accurate for the calculation of neutronic parameters of PWR reactor core benchmark. Therefore, SRAC code system can be used to calculate neutronic parameters of PWR reactor core, especially when using MOX (mixed oxide) fuel.

Keywords: Neutronic parameter, critical boron concentration, power peaking factor, SRAC code system.

ABSTRAK

VALIDASI SRAC CODE SYSTEM UNTUK PERHITUNGAN PARAMETER NEUTRONIK PADA TERAS BENCHMARK PWR MOX/UO_2. *Penentuan nilai parameter neutronik menjadi hal yang penting dalam perhitungan keselamatan reaktor sehingga bisa didapatkan hasil perhitungan yang akurat. Penelitian ini bertujuan untuk memvalidasi SRAC code system dalam penentuan nilai parameter neutronik pada teras reaktor PWR (Pressurized Water Reactor). Kasus yang dipilih adalah MOX/UO_2 Core Benchmark karena digunakan oleh beberapa peneliti sebagai acuan validasi code untuk penentuan parameter neutronik teras reaktor. Parameter neutronik yang dihitung antara lain konsentrasi boron kritis, fraksi neutron kasip dan Faktor Puncak Daya (FPD) dan profil distribusi FPD pada arah aksial dan radial. Ketika dibandingkan dengan data referensi, hasil perhitungan SRAC code system pada nilai konsentasi boron kritis, terdapat perbedaan sebesar 22.5 ppm. Sedangkan pada selisih nilai daya per perangkat bakar (assembly power error), nilai power-weighted error (PWE) dan error-weighted error (EWE) masing-masing sebesar 2.93% dan 3.94%. Selisih maksimum harga FPD arah aksial dengan referensi mencapai 4.57%. Selain itu, hasil perhitungan SRAC menunjukkan konsistensi dengan hasil perhitungan paket program atau code lain. Hasil penelitian ini menunjukkan bahwa SRAC code system masih cukup akurat dalam menghitung parameter neutronik teras benchmark reaktor PWR. Oleh karena itu, SRAC code system dapat digunakan untuk perhitungan parameter neutronik teras reactor PWR berbahan bakar MOX (mixed oxide).*

Kata kunci*: Parameter neutronik, konsentrasi boron kritis, faktor puncak daya, SRAC code system.*

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INTRODUCTION

Nuclear power plant safety analysis is a very important thing to do, especially to predict reactor behavior in both normal and abnormal conditions. Computer code that is able to accurately determine parameters required to analyze reactor safety is necessary. Therefore, computer code must be verified and validated on a variety of cases to demonstrate its reliability. The need to verify and validate becomes an important issue, especially in specially developed computer programs. For this reason, many researchers perform code validation to ensure that their results are consistent with their case [1]–[3]. This study will verify a program package called SRAC code system developed by JAERI with a deterministic method to calculate core parameters [4].

SRAC program has been used in research reactors [5], [6], cross-sections generation on the Almaraz Pressurized Water Reactor (PWR) - Unit II fuel assembly which is then used for benchmark case in fuel management of reactor core [7] and calculation of PWR AP1000 core parameters [8], [9], However, in case of using MOX/UO_2 fuel, validation is still necessary to ensure the code consistency in determining reactor parameters. For this reason, the Pressurized Water Reactor (PWR) MOX/UO_2 core transient benchmark from OECD Nuclear Energy Agency (NEA) is choosen[10]. The MOX core transient benchmark has been used several times by researchers to verify programs they are using [11], [12]. In addition, selection of PWR MOX/UO_2 core is also because MOX fuel can be used as an alternative fuel for future reactors [13]–[16]. The main advantages of having plutonium in MOX fuel are reduction in amount of enriched uranium to operate reactor and reduction of radioactive waste generated from spent nuclear fuel. However, its effect on changing neutron spectrum inside core that use MOX will change nuclear design parameters and this is related to reactor safety.

The purpose of this study was to validate SRAC program in determining PWR MOX/UO_2 core neutronic parameters. Previously, calculation of core was done in a 2-dimensional manner with SRAC code system which shown effective multiplication factor (k-eff) and control rods worth is consistent with reference, with maximum deviation of radial power fraction from reference reach 6.234%[17]. In this research, 3-D calculations will be carried out under Hot Zero Power (HZP) conditions and calculated neutronic parameters are critical boron concentration and power peaking factor in axial and radial directions. The chosen neutronic parameter is one of important parameters for safety analysis of reactor operation. The calculations were performed using 2 groups of neutron energy (2G), 4 groups (4G) and 8 groups (8G). It is very important to see sensitivity of SRAC program in determining core neutronic parameters of PWR for various neutron energy group. The calculation results will be compared with some computer code from reference [10]. It is very important to know accuracy of SRAC program in determining the safety parameters for reactor that use MOX as one of its fuels in PWR core.

The reactor core in PWR MOX/UO_2 benchmark used in this study is based on Westinghouse 3565 MWth four-loop PWR. Fuel assembly has a 17x17 pin with 193 fuels. Integral Fuel Burnable Absorber (IFBA) fuel pin is used to control reactivity of UO_2 assembly and Wet Annular Burnable Absorbers (WABA) fuel pin is used to control MOX assembly reactivity. Core configuration contains a fuel pin with 4 enrichments, namely UO_2 (4.2% and 4.5%) while MOX (4.0% and 4.3%). Active core height is 365.76 cm with various levels of burnup fraction in reactor core. ¼ core configuration is shown in Figure 1. Complete data from this benchmark can be found in reference [10].

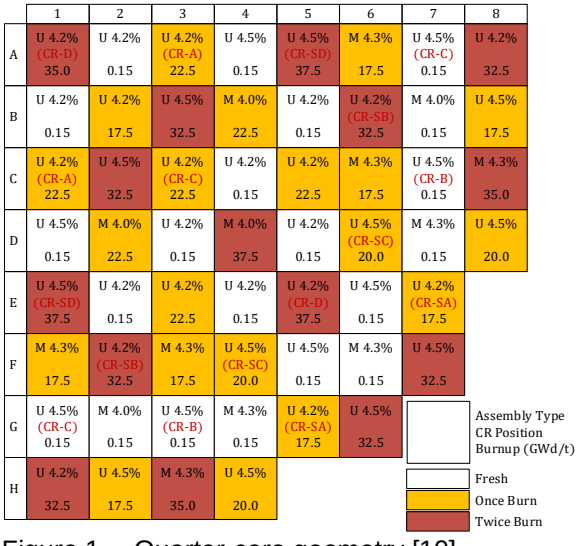

Figure 1. Quarter-core geometry [10].

Reactor core is enclosed by a reflector in axial direction with a width equal to pitch of fuel assembly. In radial direction, reflector contains 2.52 cm thick baffles and moderator

has same properties as water in reactor core. In Hot Zero Power (HZP) conditions water temperature reaches 560 K at a pressure of 15.5 MPa.

METHODOLOGY

This research flowchart is shown in Figure 2. Macroscopic cross-sections and group constants for fuel assembly are generated using the PIJ module from SRAC 2006 using material composition provided by Purdue University[18]. The PIJ module is based on neutron transport theory by using collision probability method developed at JAEA[4]. In this study, neutron energy is condensed from 107 to 2 energy groups – 2G (59 fast, 48 thermal), into 4 energy groups – 4G (28 and 31 in fast group, 11 and 37 in thermal group) and into 8 energy groups – 8G (6, 4, 18 and 17 in fast neutron group, 11, 17 and 20 in thermal neutron group) using ENDF/B-VII cross-section data. Then cross-section data and group constants for calculations on reactor core are used to model reactor core using SRAC-CITATION (2D).

Core modeling in SRAC-CITATION was carried out using baffles (2.52 cm) as in Figure 3. In 3D modeling in SRAC-CITATION, 10 mesh was used in X and Y directions of each assembly zone (21.42 cm), 4 mesh for every 22.86 cm of fuel at Z direction. ¼ core model is used for “all control banks in but all shutdown banks out” calculation, using SRAC-CITATION to find critical boron concentration, delayed neutron fraction, and Power Peaking Factor (PPF) in axial and radial direction. To achieve relative flux change for last CITATION iteration to be lower than 10^{-8}, all calculations were performed with a maximum number of iterations of CITATION, which is 999 iterations. with Hot Zero Power (HZP) conditions, at a fuel temperature of 560 K, and moderator density of 752.06 kg/m^3 (560 K).

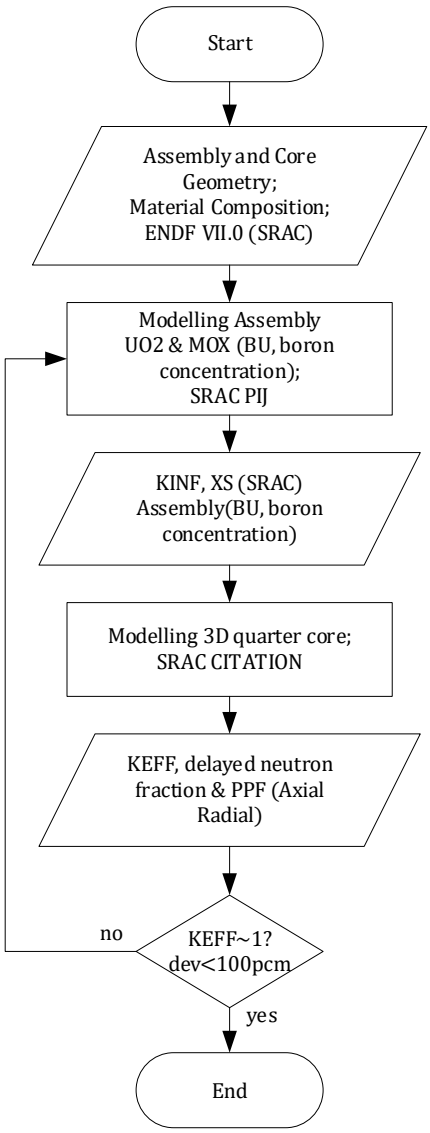

Figure 2. Calculation flowchart.

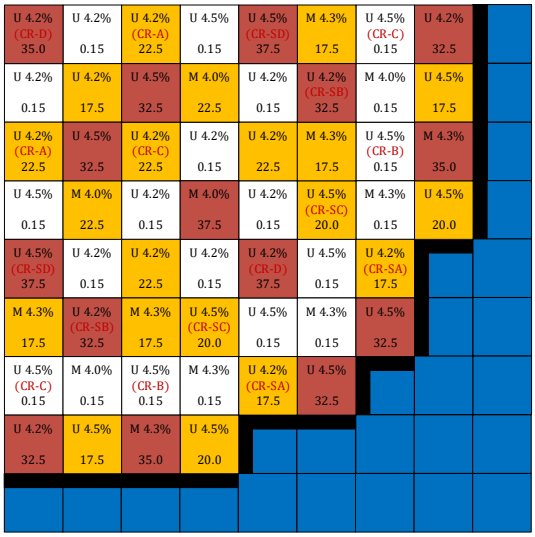

Figure 3. SRAC CITATION quarter core model using 2.52 cm baffle.

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RESULTS AND DISCUSSION

The calculation results of neutronic parameters such as critical boron concentration, delayed neutron fraction, and axial & radial direction power distribution are then compared with data calculated by DeCART as a reference [10]. To compare assembly power distribution properly in radial direction, two metrics are used to compare results, power-weighted error (PWE) and error-weighted error (EWE). Both are defined as a weighted average of error by Eq. (1) and Eq. (2), respectively, where e_i is assembly power relative error to reference data, which is defined by Eq. (3)[10].

$$PWE = \frac{\sum_i |e_i| ref_i}{\sum_i ref_i} \quad (1)$$

$$EWE = \frac{\sum_i |e_i||e_i|}{\sum_i |e_i|} \quad (2)$$

$$e_i = \frac{calc_i - ref_i}{ref_i} \times 100 \quad (3)$$

Calculation of critical boron concentration was performed in HZP conditions where all control rods were inserted and all shutdown rods were in withdrawn condition. Comparison of critical boron concentration, delayed neutron fraction and fuel assembly power error is shown in Table 1. SRAC calculations with 2G, 4G and 8G in 3D ¼ core modeling are in good agreement to reference data. Result of critical boron calculation using SRAC program when compared to DeCART reference data has a difference of 22.5 ppm. At a boron concentration of 1287.5 ppm, reactor modeling using 2G, 4G and 8G of neutron energy gave a keff of 1.000229, 1.000447, and 0.999798, respectively.

Results of critical boron calculations with SRAC program show very good results when compared to other programs in reference documents [10]. Difference in value of delayed neutron fraction calculated by SRAC with other programs such as PARCS 2G reached 3.713%, 3.640%, and 6.575% for modeling using 2G, 4G and 8G. The PWE and EWE value for SRAC are also still quite low, although not as good as other codes that use nodal solutions. In general, SRAC calculation results are in middle in terms of critical boron concentration values that are close to DeCART reference, but have a fairly small assembly power error.

Table 1. Comparison of critical boron concentration, delayed neutron fraction and assembly power error.

Code	Critical boron conc. / deviation from reference (ppm)	Delayed neutron fraction (pcm)	Assembly power error	
			%PWE	%EWE
Nodal solutions				
SRAC 2G	1287.5 / 22.5	557.500	2.930	3.949
SRAC 4G	1287.5 / 22.5	557.925	2.865	4.098
SRAC 8G	1287.5 / 22.5	540.930	3.012	4.512
EPISODE	1340 / 75	579	1.05	3.42
NEUREC	1343 / 78	576	1.05	3.43
PARCS 2G	1341 / 76	579	1.05	3.49
SKETCH-INS	1341 / 76	579	1.06	3.77
Heterogeneous solutions				
BARS	1296 / 31	579	2.65	5.66
DeCART	1265 / ref	-	ref	ref

Although assembly power error already represents how deviation of power distribution values in radial direction from reference data, Power Peaking Factor (PPF) is also an important parameter to know its value. In addition, in operation and safety analysis of PWR reactor, axial power density distribution cannot be measured directly, so it requires precision in modeling to obtain a good calculation results. PPF itself is a quantity that shows highest power fraction to average core power and its position radially & axially. Results of radial power fraction from SRAC 2G, 4G and 8G calculations when compared with DeCART reference data can be seen in Figure 4-6. Biggest difference (%absolute deviation from reference data) at SRAC 2G calculation is 6.59% in A1 position, for 4G it is 7.06% in C2 position and 8G it is 7.31% in B2 position. Based on these data, there is no

significant change in number of neutron energy group used in calculation of radial PPF because highest power fraction consistenly found in B5 and E2 position. In addition, it can be noticed that absolute deviation is consistenly increase with addition of neutron groups. This is because iteration required to achieve convergence criterion in addition of neutron groups become larger in same core geometry (mesh and zone), but maximum number of iterations in our SRAC's CITATION module is locked in 999 iterations.

	1	2	3	4	5	6	7	8
A	0.358 0.385 6.886%	0.812 0.847 4.082%	0.532 0.542 1.917%	1.547 1.510 2.423%	1.271 1.296 1.962%	1.120 1.160 3.438%	0.514 0.496 3.545%	0.281 0.293 4.015%
B	0.813 0.847 4.066%	0.814 0.871 6.541%	0.773 0.823 6.059%	1.312 1.357 3.326%	1.798 1.733 3.779%	1.041 1.073 3.027%	0.798 0.831 3.968%	0.383 0.392 2.188%
C	0.532 0.542 1.853%	0.774 0.823 6.012%	0.631 0.633 0.393%	1.603 1.563 2.542%	1.618 1.631 0.813%	1.306 1.342 2.672%	0.588 0.557 5.515%	0.313 0.324 3.478%
D	1.548 1.510 2.533%	1.313 1.357 3.234%	1.604 1.563 2.603%	1.248 1.297 3.806%	1.669 1.615 3.332%	1.455 1.462 0.505%	1.043 1.050 0.662%	0.389 0.373 4.376%
E	1.272 1.296 1.830%	1.801 1.733 3.908%	1.619 1.631 0.715%	1.670 1.615 3.399%	0.639 0.633 0.877%	1.426 1.367 4.285%	0.850 0.824 3.144%	
F	1.122 1.160 3.266%	1.042 1.073 2.864%	1.308 1.342 2.534%	1.456 1.462 0.391%	1.427 1.367 4.366%	1.101 1.089 1.136%	0.446 0.427 4.373%	
G	0.515 0.496 3.851%	0.800 0.831 3.695%	0.589 0.557 5.766%	1.045 1.050 0.475%	0.851 0.824 3.322%	0.447 0.427 4.595%		
H	0.283 0.293 3.297%	0.386 0.392 1.497%	0.315 0.324 2.871%	0.391 0.373 4.869%				

SRAC-CITATION
DeCART
%abs deviation

Figure 4. Radial power fraction results for SRAC 2G.

	1	2	3	4	5	6	7	8
A	0.365 0.385 5.321%	0.800 0.847 5.544%	0.548 0.542 1.050%	1.559 1.510 3.248%	1.297 1.296 0.062%	1.131 1.160 2.503%	0.519 0.496 4.633%	0.278 0.293 5.061%
B	0.800 0.847 5.527%	0.807 0.871 7.345%	0.779 0.823 5.380%	1.333 1.357 1.753%	1.816 1.733 4.783%	1.054 1.073 1.815%	0.786 0.831 5.440%	0.376 0.392 4.066%
C	0.548 0.542 1.120%	0.779 0.823 5.328%	0.654 0.633 3.249%	1.617 1.563 3.442%	1.634 1.631 0.179%	1.310 1.342 2.401%	0.591 0.557 6.064%	0.310 0.324 4.416%
D	1.561 1.510 3.366%	1.335 1.357 1.654%	1.618 1.563 3.508%	1.272 1.297 1.957%	1.666 1.615 3.172%	1.441 1.462 1.423%	1.015 1.050 3.326%	0.381 0.373 2.023%
E	1.299 1.296 0.206%	1.818 1.733 4.923%	1.636 1.631 0.286%	1.667 1.615 3.245%	0.653 0.633 3.112%	1.393 1.367 1.915%	0.832 0.824 1.021%	
F	1.133 1.160 2.313%	1.055 1.073 1.635%	1.312 1.342 2.249%	1.443 1.462 1.295%	1.394 1.367 2.006%	1.065 1.089 2.235%	0.437 0.427 2.450%	
G	0.521 0.496 4.986%	0.788 0.831 5.132%	0.592 0.557 6.355%	1.017 1.050 3.114%	0.834 0.824 1.225%	0.438 0.427 2.693%		
H	0.281 0.293 4.244%	0.379 0.392 3.286%	0.312 0.324 3.709%	0.383 0.373 2.582%				

SRAC-CITATION
DeCART
%abs deviation

Figure 5. Radial power fraction results for SRAC 4G.

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	1	2	3	4	5	6	7	8
	0.367	0.796	0.555	1.563	1.312	1.135	0.526	0.280
A	0.385	0.847	0.542	1.510	1.296	1.160	0.496	0.293
	4.630%	6.066%	2.344%	3.478%	1.233%	2.181%	6.122%	4.557%
	0.796	0.805	0.783	1.337	1.823	1.064	0.784	0.375
B	0.847	0.871	0.823	1.357	1.733	1.073	0.831	0.392
	6.059%	7.595%	4.859%	1.489%	5.203%	0.792%	5.673%	4.236%
	0.555	0.783	0.663	1.620	1.643	1.309	0.597	0.309
C	0.542	0.823	0.633	1.563	1.631	1.342	0.557	0.324
	2.378%	4.835%	4.724%	3.665%	0.762%	2.456%	7.135%	4.715%
	1.563	1.337	1.621	1.277	1.664	1.439	1.002	0.376
D	1.510	1.357	1.563	1.297	1.615	1.462	1.050	0.373
	3.535%	1.442%	3.698%	1.518%	3.062%	1.604%	4.565%	0.808%
	1.313	1.824	1.644	1.665	0.659	1.379	0.824	
E	1.296	1.733	1.631	1.615	0.633	1.367	0.824	
	1.306%	5.273%	0.817%	3.101%	4.041%	0.897%	0.008%	
	1.136	1.066	1.310	1.440	1.380	1.045	0.432	
F	1.160	1.073	1.342	1.462	1.367	1.089	0.427	
	2.080%	0.694%	2.372%	1.532%	0.951%	4.063%	1.174%	
	0.527	0.785	0.598	1.003	0.825	0.433		
G	0.496	0.831	0.557	1.050	0.824	0.427		
	6.339%	5.487%	7.313%	4.437%	0.125%	1.341%		
	0.281	0.377	0.310	0.377			SRAC-CITATION	
H	0.293	0.392	0.324	0.373			DeCART	
	3.988%	3.701%	4.233%	1.183%			%abs deviation	

Figure 6. Radial power fraction results for SRAC 8G.

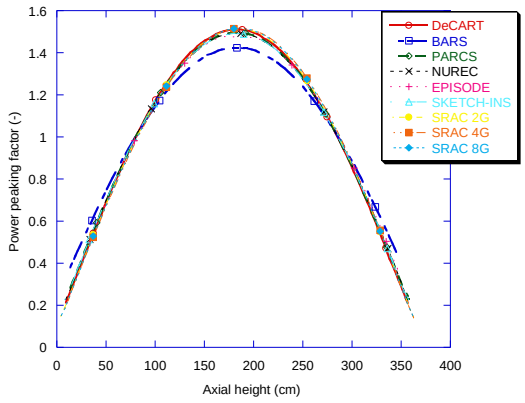

Figure 7. Axial power distribution for HZP condition.

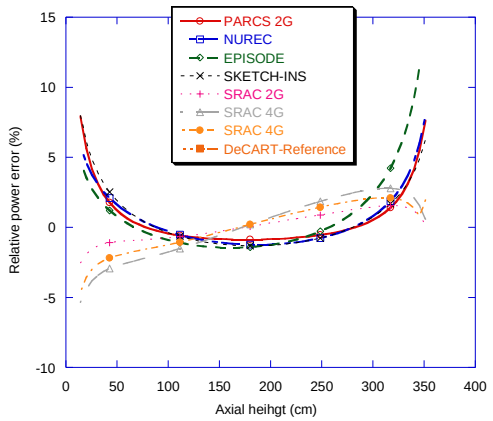

Figure 8. Axial power distribution relative error.

SRAC calculation results of axial power distribution and other programs is shown in Figure 7 and deviation of axial power distribution values against DeCART reference is shown in Figure 8. In Figure 7, it is clear that axial power distribution calculated by SRAC has same profile as reference and most other programs. However, in Figure 8, deviation of axial power from SRAC calculation results shows a different trend from other programs, which can be caused by iterations per each zone and mesh on axial power performed by SRAC's CITATION module completing iterations gradually in axial direction. This deviation is also seen to increase near axial reflector on SRAC, same as other programs that show an increase in deviation from DeCART reference near axial reflector in axial direction, but considering value is about 4-7% from DeCART, whereas in other programs deviation can be as high as 10%, it can be concluded that SRAC gives quite good results in terms of axial PPF.

CONCLUSIONS

The accuracy of SRAC Code System in calculating core neutronic parameters of the PWR MOX/UO_2 Core 3-D benchmark shows good results when compared to the DeCART reference, especially in calculating critical boron concentrations. As for assembly power error, Power Peaking Fraction (PPF) in radial

and axial directions, each has a maximum difference from reference up to 7%. When compared with other codes reported in the reference, SRAC is quite good in solving this calculation. As a final conclusion, SRAC can be used as a tool for calculating neutronic parameters on the PWR core using MOX fuel.

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AUTHOR CONTRIBUTIONS

Wahid Luthfi carried out assembly and core modelling in SRAC2006 and Surian Pinem participated as reviewer and data analysis. Wahid Luthfi is the lead author of this paper and Surian Pinem as co-author. All authors read and approved the final version of manuscript.

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