The change of radial power factor distribution due to RCCA insertion at the first cycle core of AP1000

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Abstract. The using of a computer program for the PWR type core neutronic design parameters analysis has been carried out in some previous studies. These studies included a computer code validation on the neutronic parameters data values resulted from measurements and benchmarking calculation. In this study, the AP1000 first cycle core radial power peaking factor validation and analysis were performed using CITATION module of the SRAC2006 computer code. The computer code has been also validated with a good result to the criticality values of VERA benchmark core. The AP1000 core power distribution calculation has been done in two-dimensional X-Y geometry through ¼ section modeling. The purpose of this research is to determine the accuracy of the SRAC2006 code, and also the safety performance of the AP1000 core first cycle operating. The core calculations were carried out with the several conditions, those are without Rod Cluster Control Assembly (RCCA), by insertion of a single RCCA (AO, M1, M2, MA, MB, MC, MD) and multiple insertion RCCA (MA + MB, MA + MB + MC, MA + MB + MC + MD, and MA + MB + MC + MD + M1). The maximum power factor of the fuel rods value in the fuel assembly assumed approximately 1.406. The calculation results analysis showed that the 2-dimensional CITATION module of SRAC2006 code is accurate in AP1000 power distribution calculation without RCCA and with MA + MB RCCA insertion. The power peaking factor on the first operating cycle of the AP1000 core without RCCA, as well as with single and multiple RCCA are still below in the safety limit values (less then about 1.798). So in terms of thermal power generated by the fuel assembly, then it can be considered that the AP1000 core at the first operating cycle is safe.

Keywords: Power Factor, RCCA, AP1000, SRAC2006

1. Introduction

Neutronic parameters of nuclear reactor core design safety analysis can be done through a computer program simulation. Neutronic safety design parameters of the reactor core include criticality, reactivity control rods, power distribution and others. To obtain an accurate calculation, then the computer program used must be validated. The data result of measurement through experimentation and data calculation results in the case of the benchmark can be used to validate computer codes. Validation study for several computer codes ever conducted, among others;

- Validation of the Monte Carlo code RMC with C5G7 benchmark [1],
- Validation of the Serpent-ARES codes sequence using the MIT-BEAVERS benchmark [2].
Benchmarking of the WIMS9/PARCS/TRACE code system for neutronic calculations of the Westinghouse AP1000TM reactor [3],
- Development of a MCNP-ORIGEN burn-up calculation code system and its accuracy [4],
- Comparison of nuclear data uncertainty propagation methodologies for PWR burn-up simulations [5],
- Validation of full core geometry model of the nodal3 code in the PWR transient benchmark problems [6].

Once validated, in the next step, the computer programs can be used as a tool for analyzing the safety against an existing reactor core design or to make a new core design. Several studies of nuclear reactor core analysis using a computer codes include:
- Analysis of the three-dimensional VENUS-2 MOX core benchmark using the Monte Carlo code TRIPOLI-4 [7]
- PWR experimental benchmark analysis using WIMSD and PRIDE codes [8]
- Qualification of the Taiwan Power Company’s pressurized water reactor physics methods using CASMO-4/SIMULATE-3 [9].

In this research, performed two-steps of study. The first step is to perform validation of the computer code SRAC2006 module of CITATION[10] against the value of radial power factor distribution. The second step is to analyze the changes in fuel assembly power peaking factor due to RCCA insertion. The computer code has been validated against the criticality of the core in the Virtual Environment Reactor Analysis (VERA) benchmark with good results[11]. As an object, AP1000 reactor core at the first operating cycle was used in this calculation. The AP1000 nuclear reactor is a pressurized water reactor (PWR) generation III+ type[12]. The nominal power that can be generated is 1000 MWe. As moderator and coolant are light water (H$_2$O). In the AP1000, the H$_2$O pressurized about 2250 psia or 153 atm to prevent boiling at the high temperatures (T≈325 °C). The reactor core is composed of 157 fuel assemblies. The fuel assembly provided with 24 guide tubes used for Pyrex or Rod Cluster Control Assembly (RCCA) insertion. The inserted RCCA position is among the 256 fuel rods in the fuel assembly. The insertion of RCCA in the core causing material changes contained in the fuel assembly. These material changes will affect to the distribution of radial power factor generated.

Material changes before and after RCCA insertion (H$_2$O into Ag-In-Cd/SS304) will also influence to the power peaking factor. Changes in maximum power factor need to be known so that the reactor core can operate safely ascertained by meeting the safety criteria design that have been set. The of power factor distribution calculation was carried out on 2-dimensional geometry $\frac{1}{4}$ part model of the core using of CITATION module. As input to the calculation module, in addition to the data size and geometry of core, fuel assembly macroscopic cross-sectional data is also needed. The cross-section data obtained through the calculation using PJ module. As the output from the core calculation, it will obtain the radial thermal power at the each of fuel assemblies. Power factor calculation was done on several core conditions. The first is the AP1000 core without RCCA. The second is the AP1000 core with single RCCA insertion (AO, M1, M2, MA, MB, MC, and MD). And, the thirdly is the AP1000 with multiple insertion condition of RCCA (MA + MB, MA + MB + MC, MA + MB + MC + MD and MA + MB + MC + MD + M1). As a validation, the calculation results of the core without RCCA conditions and with the bank of multiple RCCA (MA + MB) were compared with an existing data. From the analysis of the distribution of the power factor, it is expected to know the level of accuracy of the SRAC2006 computer program and the safety level of AP1000 core on the first operating cycle power factor value in terms of maximum power generated by fuel assembly.

2. Methodology
In this research, the radial power distribution calculating the fuel assemblies in the first operating cycle AP1000 core. The calculation was done using the computer program SRAC2006 CITATION module. The calculation steps are the preparation of fuel assembly data model, macroscopic cross-section calculation, reactor core modelling, and core calculation.
2.1. Calculation of the macroscopic cross-section of the fuel assembly

Calculation of fuel assembly macroscopic cross section is done using the SRAC2006 code module of PIJ. The calculation is done by condensing the energy groups of 107 into 8 groups. The cross-section library data used is SRACLIB-EDF70. The calculations were done by modeling 1/4 part of the fuel assembly. As a result of the calculation is the tables of macroscopic cross-section data in the 8 energy groups. As input calculation is the atoms density of the materials, temperature, dimensional and the size fuel assemblies, mesh division and others. A 2-dimensional model of AP1000 fuel assemblies shown in Figure 1. The size of the fuel assemblies is 21.504 cm x 21.504 cm. The fuel assembly shaped 17 x 17 grid cell consists of 264 fuel lattice cells, 24guide tube, one instrument tube and light water (H2O) as a moderator. In the guide tube will be filled with H2O, Pyrex or absorber Ag-In-Cd / SS304, depending on operating conditions of core. As shown in Figure 2, fuel lattice cells in the AP1000 reactor core has a square shape with a size of 1.260 cm x 1.260 cm. Standard fuel lattice cell composed from UO2 pellets (enrichment of 2.350%, 3.400% or 4.450%) with a radius of 0.410 cm, gap 0.426 cm, cladding ZIRLO 0.483 cm and the outer part is the moderator H2O. While in Integrated Fuel Burnable Absorber (IFBA), then there ZrB2 thin layer on the outside of UO2 pellets. ZIRLO cladding composition is Zr of 97.850%, Fe of 0.150%, Sn of 1.000%, and Nb of 1.000%. Pyrex lattice cell composed from the inner tube, the absorbent material that is borosilicate glass (B2O3-SiO2), the outer tube, and the guide tube. Control rod of lattice cells consists the absorbent material Ag-In-Cd/ SS304, cladding, and guide tube. Material composition and size of the control rods are shown in Table 1. At the time of insertion RCCA, then guide tube cell lattice would have 24 control rods Ag-In-Cd (black absorber), or 12 AG-In-Cd + 12 SS304 (gray absorber).
| Material Composition (Number) | Pyrex | Black Absorber | Gray Absorber |
|-------------------------------|-------|----------------|---------------|
| Poison Density (g/cm³)        |       | 10.158         | 10.158        |
| Inner tube (cm)               |       |                |               |
| Inner tube material           |       | SS304          |               |
| Poison Radius (cm)            | 0.461 (ID) / 0.968 (OD) | 0.433          | 0.4064        |
| Cladding material (cm)        |       | SS304          |               |
| Clad thickness (cm)           |       | 0.047          |               |
| Guides Tube inner diameter (cm) |       | 1.008          |               |
| Guides Tube Outer Diameter (cm) |       | 1.224          |               |

2.2. The Thermal Power Factor Calculation

Figure 3 shows a model of the ¼ part on the first AP1000 operating cycle with the distribution of fuel assemblies and control rod cluster. The first line shows the type of fuel that the fuel assemblies with enrichment UO₂ 2.350%, 3.400% or 4.450%. The second line is the amount of fuel IFBA located on each of the fuel assemblies. The third line shows the RCCA type or number of Pyrex contained in fuel assemblies.

In the AP1000, control rod bank classification can be divided into 11 groups:

1. MA (Mechanical Shim Gray Bank A): 4 Clusters
2. MB (Mechanical Shim Gray Bank B): 4 Clusters
3. MC (Mechanical Shim Gray Bank C): 4 Clusters
4. MD (Mechanical Shim Gray Bank D): 4 Clusters
5. M1 (Mechanical Shim Black Bank 1): 4 Clusters
6. M2 (Mechanical Shim Black Bank 2): 8 Clusters
7. AO (Axial Offset Control Bank): 9 Clusters
8. SD1 (Shutdown Bank 1): 8 Clusters
9. SD2 (Shutdown Bank 2): 8 Clusters
10. SD3 (Shutdown Bank 3): 8 Clusters
11. SD4 (Shutdown Bank 4): 8 Clusters

In accordance with the document control rev.19, the AP 1000 core calculation performed with the insertion RCCA condition as follows; MA + MB, MA + MB + MC, MA + MB + MC + MD, and MA + MB + MC + MD + M1. In addition, the core calculation with the conditions of each insertion RCCA includes AO, M1, M2, MA, MB, MC, and MD. While RCCA SD1 to SD4 were not be calculated. Those RCCA have to serve the shutdown of the reactor. At the time of shut-down reactor, the reactor core power is 0.
Calculation of fuel power distribution of fuel assembly in the first operating cycle of AP1000 was carried out on the two-dimensional geometry of ¼ part core model. The core model, in addition to the fuel assembly, also consists of another material. The material from the inside to the outside of the core are the baffle reactor, cooling made from light water H₂O, barrel reactor, and the reactor vessel. Baffle reactor is outside the blanket that surrounds the entire fuel assembly with SS304 material. Core barrel reactor is a tube bulkhead separation between the coolant flow and the inner reactor with size d_in / d_out 339.725 cm / 349.885 cm, made from SS304 material. And the reactor vessel is a container from all parts of the reactor core material with a size d_in / d_out 398.800 cm / 420.100 cm SS304 material.

3. Results and Discussion
Figure 4 shows a comparison of radial power factor distribution at the first cycle of AP1000 core without RCCA condition. The first line shows the type of fuel. Number 1, 2 and 3 are the UO₂ fuel enriched about 2.350%, 3.400% and 4.450%, respectively. While the letter P and I are the numbers of Pyrex and IFBA. The second line is the value of the power factor reference data are the result of calculations with computer program ANC (A Westinghouse Advanced Nodal Computer Code.) The third line is the value of the distribution of power factor calculation results with computer program SRAC2006 CITATION module. The fourth line is the value of the difference between the reference data with the value of the calculation result. While row five is percent difference value.
Figure 4. Radial power factor distribution at the first cycle of AP1000 core without RCCA

The fuel assembly radial power peaking factor value from the reference data is 1.232, namely fuel with enrichment 2.350% at H-8 position. In the same position, the calculation results show the value of 1.279 or the difference in -0.047 (-38.15%). It is due to the H-8 position in the center of the core. In addition, although the fuel assemblies having a low enrichment (2.35%), but there are no Pyrex and IFBA absorbent material inside. Fuel assembly at the center of core, in addition to the absence of of strong absorbent materials, the largest thermal flux neutrons are also produced. Most of the thermal neutrons absorbed by the fuel will react with U-235 fission. So the fuel assembly in the position of H-8 produces the greatest thermal power.

The highest power factor value is still below the design limit. Design limitations specified value is hot channel factor of 2.62. The value is the highest power of the fuel rods divided by average power
value of all fuel rod in the cores. Based on reference data, then at the beginning of the cycle indicates
the value of the fuel rod radial power peaking factor in the fuel assembly is approximately about
1.406. So that when multiplied by the highest radial power factor produces by fuel assembly become a
value of 1.798. That is still far below the maximum limit value of 2.600. On AP1000 core with a
power of 3400 MW, the average linear power is 18.760 kW / m. While the peak value of the fuel rod
linear power is 49.260 kW/m. So that the power factor of the fuel rods is about 2.60. At the near
beginning of life, unrodded, hot full power, and no xenon condition of core, then the F-DELTA-H value
is 1.406. F-DELTA-H is defined as the ratio between the thermal power integral fuel rods divided by
the average power of all fuel rod.

Lowest power factor value is equal to 0.454 at position A-9. This occurs because although the
UO$_2$ fuel assemblies with enrichment 4.450%, but is at a position on the edge of the IFBA number in
which there were 112 among 264 pellets. The highest difference between the value of the reference
data and the calculation results amounted to 6.250% (grid position D-13) is a device UO$_2$ fuel
enrichment 4.45% with 112 IFBA. So it can be said that the SRAC2006 code CITATION module valid for the calculation of the radial power factor of AP1000.

| H  | G   | F   | E   | D   | C   | B   | A   |
|----|------|-----|-----|-----|-----|-----|-----|
| 1.336 | 1.187 | 1.302 | 1.166 | 1.292 | 1.127 | 0.725 | 0.469 |
| 1.252 | 1.158 | 1.224 | 1.152 | 1.237 | 1.110 | 0.720 | 0.491 |
| 0.084 | 0.029 | 0.078 | 0.014 | 0.055 | 0.017 | 0.005 | -0.022 |

Figure 5. Radial power factor distribution at the first cycle of AP1000 core with multiple (MA+MB)
RCCA inserted
Radial power factor distribution at the first cycle of AP1000 core with the insertion of multiple RCCA (MA + MB) showed in Figure 5. Radial power factor value of the fuel assembly reference data is shown on the first line, the result of the calculation using CITATION module of SRAC2006 on the second line. Differences are both shown in the 3rd row, percent of differences shown in the 4th row. The lowest differences power factor value is 0.003 (H-13) with a difference ratio of 0.414%. At the position of H-13 and B-8 is a 3.40% enrichment UO$_2$ fuel assemblies with 24 Pyrex 88 IFBA, and their insertion of RCCA is bank MB. A number of absorbent materials that cause a little difference between reference data and calculation results. At the RCCA bank, MA insertion position F-10 that there is a difference greater than the position RCCA bank MB. In addition to differences in the position of MA more inner of the core, also due to the absence of absorbent material such as Pyrex and/or IFBA on the position. The biggest difference between the reference data and the calculation results shown by the fuel assemblies in the position of H-8 is about 0.084. Position H-8 is located right in the mid of core, and an enrichment UO$_2$ fuel assembly is 2.350% without Pyrex and IFBA. This causes the thermal neutron flux is higher towards the middle of the core. While the ratio of the largest difference occurs at position C-12 and D-13 that is about -8.876%. So that the power factor calculation AP1000 core with multiple RCCA insertions conditions. Calculation using CITATION module of the SRAC2006 computer code can also be said to be valid.

|    | H     | G     | F     | E     | D     | C     | B     | A     |
|----|-------|-------|-------|-------|-------|-------|-------|-------|
| 8  | 1.232 | 1.150 | 1.225 | 1.138 | 1.215 | 1.151 | 0.941 | 0.572 |
|    | 0.659/AO |     |     |     |     |     |     |     |
|    | 1.413 | 1.294 | 1.285 | 0.964 | 0.539/M1 | 0.899 | 0.830 | 0.563 |
|    | 1.687 | 1.572 | 1.605 | 1.396 | 1.389 | 1.246 | 0.997 | 0.605 |
| 9  | 1.151 | 1.229 | 1.242 | 1.211 | 1.119 | 1.138 | 0.527 | 0.454 |
|    | 1.116 | 1.311 | 1.272 | 1.267 | 1.071 | 1.244 | 0.146 | 0.605 |
|    | 1.294 | 1.368 | 1.212 | 1.147 | 0.924 | 1.017 | 0.177 | 0.452 |
|    | 1.572 | 1.653 | 1.465 | 1.446 | 1.225 | 1.168 | 0.937 | 0.467 |
| 10 | 1.225 | 1.143 | 1.212 | 1.119 | 1.178 | 1.028 | 0.892 | 0.691 |
|    | 1.390 | 1.273 | 1.275 | 0.978 | 0.571/AO | 0.926 | 0.926 | 0.605 |
|    | 1.286 | 1.212 | 1.299 | 1.177 | 1.212 | 1.059 | 0.885 | 0.647 |
|    | 1.605 | 1.465 | 1.466 | 1.226 | 1.121 | 0.848 | 0.691 | 0.405 |
| 11 | 1.138 | 1.212 | 1.119 | 1.169 | 1.047 | 1.081 | 0.584 | 0.610 |
|    | 1.284 | 1.268 | 0.979 | 0.975 | 0.828 | 0.788 | 0.369 | 0.648 |
|    | 0.964 | 1.148 | 1.177 | 1.287 | 1.165 | 1.206 | 0.647 | 0.775 |
|    | 1.397 | 1.446 | 1.227 | 1.125 | 0.809 | 0.463/M2 | 0.348 | 0.348 |
| 12 | 1.216 | 1.120 | 1.179 | 1.047 | 0.801 | 0.463/M2 | 0.348 | 0.348 |
|    | 1.365 | 1.074 | 0.572/AO | 0.829 | 0.788 | 0.648 | 0.775 | 0.369 |
|    | 0.539/M1 |     |     |     |     |     |     |     |
|    | 0.925 | 1.213 | 1.166 | 0.990 | 0.775 | 0.369 | 0.369 | 0.369 |
| 13 | 1.153 | 1.140 | 1.030 | 1.082 | 0.672 | 0.672 | 0.672 | 0.672 |
|    | 1.373 | 1.248 | 0.928 | 0.649 | 0.649 | 0.649 | 0.649 | 0.649 |
|    | 0.901 | 1.019 | 1.060 | 1.207 | 0.776 | 0.776 | 0.776 | 0.776 |
|    | 1.249 | 1.471 | 0.850 | 0.369 | 0.369 | 0.369 | 0.369 | 0.369 |
| 14 | 0.944 | 0.930 | 0.831 | 0.585 | 0.585 | 0.585 | 0.585 | 0.585 |
|    | 1.223 | 1.152 | 0.930 | 0.611 | 0.611 | 0.611 | 0.611 | 0.611 |
|    | 0.883 | 0.889 | 0.867 | 0.648 | 0.648 | 0.648 | 0.648 | 0.648 |
|    | 1.001 | 0.940 | 0.693 | 0.349 | 0.349 | 0.349 | 0.349 | 0.349 |
| 15 | 0.576 | 0.457 | 0.457 | 0.457 | 0.457 | 0.457 | 0.457 | 0.457 |
|    | 0.787 | 0.611 | 0.611 | 0.611 | 0.611 | 0.611 | 0.611 | 0.611 |
|    | 0.567 | 0.453 | 0.453 | 0.453 | 0.453 | 0.453 | 0.453 | 0.453 |
|    | 0.610 | 0.471 | 0.471 | 0.471 | 0.471 | 0.471 | 0.471 | 0.471 |

Figure 6. Radial power factor distribution at the first cycle of AP1000 core with single AO, M1, M2 RCCA inserted
Radial power factor distribution at the first cycle of the AP1000 core with the insertion of single RCCA ((AO, M1, M2) and (MA, MB, MC, MD)) showed at the Figure 6 and 7, respectively. In Figure 6, line 1, 2, 3 and 4 row are AP1000 power factor in the current conditions without RCCA, with the insertion of RCCA AO, M1, and M2, respectively. In Figure 7, line 1, 2, 3 and 4 are AP1000 power factor in the current conditions without RCCA, with insertion RCCA of MA, MB, MC, and MD, respectively.

As it is known that the AO, M1, and M2 is a black absorber with 24 control rods are Ag-In-Cd. While the MA, MB, MC and MD are gray absorber with 12 control rods SS304 and 12 Ag-In-Cd. Of the two pictures can be seen changes in the value of the power factor of the fuel assemblies in each of the control rod positions before and after insertion. At the time of insertion AO at position H-8, D-10, and F-12 changes the value of the power factor respectively amounted to 46.510%, 51.484%, 51.528% and. At the time of insertion M1 (D-8 and H-12) changes the value of the power factor in a row and amounted to 55.638%, 55.674%. At the time of insertion M2 (C-11 and E-13) changes the value of the power factor in a row and amounted to 57.169%, 57.116%. Although the material is inserted at (Ag-In-Cd), but at each position will produce different power factor. The analysis showed that more toward the outside of the core, then change the value of the power factor will be slightly larger. It is caused by the influence of the magnitude of the thermal neutron flux at each of these positions.

From Figure 6b, it is known that at the time of insertion MA of F-10 changes the value of the power factor of 25.743%. At the time of insertion MB at position B-8 and H-14 changes the value of the power factor in a row and amounted to 29.224%, 29.237%. At the time of insertion, MC position D-12 changes the value of the power factor of 25.668%. At the time of insertion of the MD position F-8 and -10 changes the value of the power factor in a row and amounted to 30.939%, 30.939%. Judging from the position RCCA inside the core, then from the inside to the outside is MD, MB, MA, and MC. When viewed from the power factor changes, then the MD and MB greater than the MA and MC. As it is known that RCCA MA, MB, MC, and MD are gray absorbers which are 12 Ag-In-Cd and 12 SS304. So apart from a neutron absorbing material, effect SS304 to reducing the amount of moderator in the fuel assemblies. So that the neutron moderated from the rapid energy to thermal energy will also be reduced. As a result of fuel assemblies in the position of insertion RCCA MA and MC which only amounted to one RCCA will be slightly smaller than the position RCCA MD and MB.

From Figure 6.a and 6.b it can be seen that the power factor changes on the fuel assemblies in the position of insertion RCCA AO, M1 and M2 showed a larger value then MA, MB, MC, and MD. As mentioned before that RCCA AO, M1, and M2 named with black absorbers that the material consists of 24 rods of Ag-In-Cd. While RCCA MA, MB, MC, and MD are named with gray absorbers, that are consist of 12 rods of Ag-In-Cd and 12 rods of SS304.
Radial power factor distribution at the first cycle of AP1000 core with the insertion of the multiple RCCA showed in Figure 8. Row 1, 2, 3, 4, 5 and 6 show power factor value in the first operating cycle of AP1000 without RCCA insertion RCCA banks MA, MA + MB, MA + MB + MC, MA + MB + MC + MD and MA + MB + MC + MD + M1, respectively. Power peaking factor value on each condition without RCCA is 1.232 (position H-8), with insertion of MA RCCA is 1.240 (position H-12 symmetrical with the D-8), with insertion of MA + MB is 1.252 (position H-8), with insertion of MA + MB + MC is 1.347 (the position of the D-8), with insertion of MA + MB + MC + MD is 1.274 (the position of the G-8, symmetrical with C-9) and with insertion of MA + MB + MC + MD + M1 is 1.323 (position E-11). The biggest difference is at the insertion of MA + MB + MC.
RCCA from 1.232 (condition without RCCA) to 1.347 or an increase of 9.334%. It is caused by the insertion position RCCA MC is on the D-12 which is located alongside a relative inactive of the core. So that the thermal neutron flux will be enlarged in the center of the core position. At each addition RCCA an increase in maximum power factor value than before insertion RCCA. The maximum value of the power factor is still meet the safety, well below the thermal design power factor of the fuel assembly (approximately 1.8).

|     | H    | G    | F    | E    | D    | C    | B    | A    |
|-----|------|------|------|------|------|------|------|------|
|     | 1.252 | 1.150 | 1.225 | 1.138 | 1.215 | 1.151 | 0.941 | 0.572 |
|     | 1.141 | 1.060 | 1.137 | 1.100 | 1.239 | 1.218 | 1.018 | 0.625 |
|     | 1.292 | 1.139 | 1.326 | 1.237 | 1.237 | 1.237 | 0.728/MB | 0.492 |
|     | 1.347 | 1.241 | 1.299 | 1.207 | 1.284 | 1.146 | 0.743 | 0.508 |
|     | 1.063 | 0.961 | 0.887/M | 1.082 | 1.293 | 1.216 | 0.810 | 0.561 |
|     | 1.195 | 1.058 | 0.887 | 0.889 | 0.564/M | 0.958 | 0.772 | 0.568 |
| 8   | 1.151 | 1.121 | 1.132 | 1.211 | 1.119 | 1.138 | 0.927 | 0.454 |
|     | 1.061 | 1.114 | 1.016 | 1.151 | 1.135 | 1.203 | 1.000 | 0.495 |
|     | 1.158 | 1.213 | 1.092 | 1.207 | 1.145 | 1.140 | 0.871 | 0.415 |
|     | 1.241 | 1.294 | 1.152 | 1.254 | 1.176 | 1.166 | 0.892 | 0.427 |
|     | 0.961 | 1.035 | 0.564 | 1.175 | 1.198 | 1.244 | 0.974 | 0.471 |
|     | 1.059 | 1.117 | 0.987 | 1.081 | 0.987 | 1.131 | 0.964 | 0.484 |
| 9   | 1.225 | 1.143 | 1.212 | 1.119 | 1.178 | 1.028 | 0.829 | 0.454 |
|     | 1.137 | 1.017 | 0.900/M | 1.036 | 1.193 | 1.083 | 0.890 | 0.454 |
|     | 1.225 | 1.092 | 0.960 | 1.089 | 1.225 | 1.077 | 0.856 | 0.415 |
|     | 1.300 | 1.152 | 0.995 | 1.100 | 1.217 | 1.069 | 0.655 | 0.427 |
|     | 0.988 | 0.995 | 0.986 | 1.091 | 1.272 | 1.253 | 0.857 | 0.484 |
|     | 1.138 | 1.212 | 1.119 | 1.169 | 1.047 | 1.081 | 0.584 | 0.454 |
|     | 1.101 | 1.152 | 1.037 | 1.138 | 1.071 | 1.140 | 0.624 | 0.454 |
|     | 1.152 | 1.288 | 1.089 | 1.134 | 1.114 | 1.148 | 0.528 | 0.454 |
|     | 1.207 | 1.255 | 1.100 | 1.152 | 1.026 | 1.095 | 0.605 | 0.454 |
|     | 1.083 | 1.176 | 1.092 | 1.193 | 1.085 | 1.193 | 0.666 | 0.454 |
|     | 0.896 | 1.081 | 1.342 | 1.323 | 1.233 | 1.356 | 0.755 | 0.454 |
| 10  | 1.216 | 1.120 | 1.179 | 1.047 | 0.861 | 0.671 | 0.671 | 0.454 |
|     | 1.240 | 1.137 | 1.194 | 1.071 | 0.897 | 0.709 | 0.736 | 0.454 |
|     | 1.052 | 1.146 | 1.096 | 1.154 | 1.036 | 0.936 | 0.671 | 0.454 |
|     | 1.285 | 1.177 | 1.218 | 1.027 | 0.693/MC | 0.631 | 0.693/MC | 0.454 |
|     | 1.295 | 1.199 | 1.273 | 1.055 | 0.751 | 0.692 | 0.751 | 0.454 |
|     | 0.565/M | 0.988 | 1.321 | 1.232 | 0.876 | 0.814 | 0.876 | 0.454 |
| 11  | 1.193 | 1.140 | 1.062 | 1.062 | 0.672 | 0.672 | 0.672 | 0.454 |
|     | 1.212 | 1.205 | 1.085 | 1.141 | 0.709 | 0.709 | 0.709 | 0.454 |
|     | 1.111 | 1.141 | 1.078 | 1.180 | 0.736 | 0.736 | 0.736 | 0.454 |
|     | 1.148 | 1.167 | 1.070 | 1.056 | 0.632 | 0.632 | 0.632 | 0.454 |
|     | 1.218 | 1.274 | 1.154 | 1.194 | 0.692 | 0.692 | 0.692 | 0.454 |
|     | 0.959 | 1.133 | 1.242 | 1.357 | 0.814 | 0.814 | 0.814 | 0.454 |
| 12  | 0.944 | 0.930 | 0.831 | 0.585 | 0.585 | 0.585 | 0.585 | 0.454 |
|     | 1.022 | 1.003 | 0.892 | 0.625 | 0.625 | 0.625 | 0.625 | 0.454 |
|     | 0.722/M | 0.873 | 0.857 | 0.628 | 0.628 | 0.628 | 0.628 | 0.454 |
|     | 0.745 | 0.894 | 0.857 | 0.606 | 0.606 | 0.606 | 0.606 | 0.454 |
|     | 0.813 | 0.977 | 0.939 | 0.667 | 0.667 | 0.667 | 0.667 | 0.454 |
|     | 0.775 | 0.967 | 1.005 | 0.756 | 0.756 | 0.756 | 0.756 | 0.454 |

**Figure 8.** Radial power factor distribution at the first cycle of AP1000 core with multiple RCCA inserted

### 4. Conclusion

From the calculation result analysis, it can be concluded that the SRAC2006 code CITATION module valid for the calculation of the radial power factor of AP1000. Insertion of RCCA caused increasing power peaking factor of the fuel assembly. The value of the fuel rod radial power peaking factor in the
fuel assembly is assumed approximately about 1.406. Then the value of fuel assembly power peaking factor in the core still has below the design criteria, 2.600. In the case of power thermal produced by fuel assembly, therefore the AP1000 core can be operated safely.

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References
[1] GaoB, MaXB, ChenYX, YuH2013 Validation the Monte Carlo code RMC with C5G7 benchmark Nuclear Engineering and Design 265 64
[2] Leppänen J, Mattila R, Pusa M 2014 Validation of the Serpent-ARES codes sequence using the MIT-BEAVERS benchmark – initial core at HZP conditions Annals of Nuclear Energy 69 212
[3] ElsawiMA, HraizAS B 2015 Benchmarking of the WIMS9/PARCS/TRACE Code System for Neutronic Calculations of The Westinghouse AP1000TM Reactor Nuclear Engineering and Design 293 249
[4] Zheng M, Tian W, Wei H, Zhang D, Wu Y, Qiu S, Su G 2014 Development of a MCNP–ORIGEN burn-up calculation code system and its accuracy assessment Annals of Nuclear Energy 63 491
[5] DiezCJ, Buss O, Hoefer A, Porsch D, Cabellos O 2015 Comparison of nuclear data uncertainty propagation methodologies for PWR burn-up simulations Annals of Nuclear Energy 77 101
[6] Sembiring T M, Pinem S, Liem P 2015 Validation of full core geometry model of the nodal3 code in the PWR transient benchmark problems Journal of Nuclear Reactor Technology TRI DASA MEGA 17 141
[7] Savva P, Varvayanni M, Catsaros N 2014 Analysis of the three-dimensional VENUS-2 MOX core benchmark using the Monte Carlo code TRIPOLI-4 and the ENDF/B-VI.4, ENDF/B-VII.0 and JEFF-3.1 nuclear data sets Nuclear Engineering and Design 273 215
[8] Arshad F, Ahmad S, Haq I 2014PWR experimental benchmark analysis using WIMSD and PRIDE Codes Annals of Nuclear Energy 72 11
[9] Lin H C, Yaur S J, Lin T Y, Kuo W S, Shine J Y, Huang Y 2012 Qualification of the Taiwan Power Company’s Pressurized Water Reactor Physics Methods Using CASMO-4/SIMULATE-3 Nuclear Engineering And Design 253 71
[10] Keisuke O, Teruhiko K, Kunio K and Keichiro T 2007 SRAC2006: A Comprehensive Neutronics Calculation Code System JAEA-ading/Code-2007-004 Japan Atomic Energy Agency
[11] Susilo J 2014 Verification of MVP-II and SRAC06 Code for the Case VERA Benchmark Reactor Core Journal of Nuclear Reactor Technology TRI DASA MEGA 1675
[12] Anonim AP1000 Design Control Document Revision 19 Chapter 4.3 Nuclear Design Westinghouse Electric, USA Available from website: https://www.nrc.gov/docs/ML1117/ML11171A445.pdf Accessed: February 20, 2017.