Pwr Fuel Macroscopic Cross Section Analysis for Calculation Core Fuel Management Benchmark

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Abstract. The in-core fuel management of PWR reactor is very complex because the core is loaded by several enrichments as well as the number and types of burnable poison rod (pyrex) of the fuel assemblies. Besides that, the boron content in the moderator rely on the operation condition. Therefore, the core calculation requires macroscopic neutron cross section representing each type of fuel assemblies and operating conditions. The evaluation of in-core fuel management in the PWR needs a validated code. The PWR-FUEL code has been verified on the criticality cases and showed a satisfaction results. However, the code is not yet validated with the benchmark in-core fuel management cases. This study aims to generate the macroscopic cross sections for the fuel assemblies of PWR Almaraz Unit II which used as a benchmark case for the in-core fuel management that described in the IAEA-TECDOC-815. The cross sections are generated by using the SRAC2006 core which has been used in the criticality analysis of AP1000 reactor. The calculation results showed that the cross section is accurate since the maximum difference value of $k_{inf}$ is 1.87%.

Keywords: PWR, in-core fuel management, macroscopic neutron cross section, benchmark, SARC2006

1. Introduction

In support of the nuclear R & D program, especially for the first nuclear power plant in Indonesia, BATAN as a nuclear R & D institution has undertaken several planned and sustainable phases. BATAN has been developing NODAL3 codes for determine neutronic and thermal-hydraulic parameters of Pressurized Water Reactor (PWR). The NODAL3 code has been validated for static and transient PWR-type reactor[1–4]. Furthermore, it is necessary to evaluate the core fuel management for optimization of fuel and reactor operation safety. The PWR-FUEL code has been developed for PWR core management based on 3-dimensional nodal method [5]. The program has been verified [6] and the accuracy needs to be validated with the benchmark case.

Calculation of core fuel management is very important role in the safety of PWR reactors because through this calculation can determine the fuel element efficiency, maximum power peaking factor, in each fuel assembly or fuel rod, flux neutron, boron concentration and fuel fraction per fuel assembly [7]. Type of fuel element is large and varied in the PWR core, the usual calculation of core management is done by nodal method by solving the multi-group neutron diffusion equations in 3-dimensional (3-D) Cartesian geometry. Calculation of core fuel management is still developing, especially in the optimization of fuel loading in the core [8–10].

For PWR core, operating parameters that influential in the core fuel management calculations are fuel temperature, moderator temperature and boron concentration. In the calculation of the depletion of fissile material a concentration of each split nuclide for each level of the burn up as well as each operating condition (temperature and boron concentration) shall be provided. In addition, the
complexity of fuel management on PWR core is due to the enrichment types, burnable poison configurations and different types burnable poison for each fuel assembly [11]. Therefore, the accuracy of the core fuel management computer package is highly dependent on the macroscopic cross section data [11–14].

Before used for PWR core management, in-core fuel management code need to be validated with a benchmark containing the core management case. The PWR core management benchmark case is not widely publicized, except those presented by the IAEA within the IAEA-TECDOC-815 [15]. The benchmark case presented is the result of the experimental operation of the PWR Almaraz Unit-II (in Spain) reactor having a thermal power of 2686 MW. In this benchmark case, no macroscopic cross section, or diffusion constant, were given the only available data are fuel assembly data and other operating reactor data [15]. Therefore, before doing the calculation of the core fuel management, cross section generation should be performed for each core material with high accuracy. The research activities aimed to generate the macroscopic cross section data of PWR fuel used in the PWR core management benchmark case, Almaraz Unit II reactor.

The benefit of this research is to obtain an accurate methodology in preparing the macroscopic cross section data of PWR fuel. The cross section generation of PWR fuel is carried out with the SRAC2006 program package[16]. In an accuracy analysis, the value of kinf (infinity multiplication factor) of fuel cells is determined. In the future research will be continued by determining the macroscopic cross section derivative, core calculation and core fuel management.

2. Almaraz II PWR Core Description
PWR Almaraz Unit II (Almaraz-II) core consists of 157 pieces of fuel assembly whose fuel rods are arranged in the form of $17 \times 17$. Each assembly is composed of 264 fuel rods. Table 1 shows some data of Almaraz-II core.
### Table 1. Design parameters of Almaraz-II core [15]

| Core Description                        | Value                     |
|----------------------------------------|---------------------------|
| **Thermal power, MW**                  | 2686                      |
| Heat generated in fuel, %              | 97.4                      |
| **Coolant**                            |                           |
| Hot full power (HFP) inlet temperature, °C | 291.4                    |
| Hot full power (HFP) average core outlet temperature, °C | 326                   |
| Hot full power (HFP) average moderator temperature, °C | 309.9               |
| Hot full power (HFP) average fuel cladding temperature, °C | 340              |
| Hot full power (HFP) average fuel temperature, °C | 654                 |
| Hot full power (HFP) effective fuel temperature BOL (beginning of life) & HFP, °C | 640            |
| **Core**                               |                           |
| Number of batch for initial core       | 3                         |
| Uranium enrichment for first cycle, %  | 2.1; 2.6; 3.1             |
| **Pellet**                             |                           |
| Material                               | UO₂                       |
| Density (percent of theoretical)       | 95%                       |
| Radius, cm                             | 0.4096                    |
| Pellet length, cm                      | 1.346                     |
| Height of UO₂, in rod, cm              | 365.76                    |
| **Burnable Poison Rod**                |                           |
| Material to hold absorber              | Pyrex-l assassin          |
| Fraction of B in material (B₂O₃), w/o | 12.5                      |
| Mass of 10B per unit length of rod, g/cm | 0.006234             |
| Active length, cm                      | 359.562                   |
| Outside thickness, cm                  | 0.48387                   |
| Clad thickness, cm                     | 0.04699                   |
| Clad material                          | SS-304                    |
| Inner tube material                    | SS-304                    |
| Inner tube outside radius, cm          | 0.2305                    |
| Inner tube thickness, cm               | 0.01651                   |
| **Configuration**                      |                           |
| Reactor Core                           | Figure 1                  |
| Pyrex in fuel assembly                 | Figure 2                  |
| Control rod in the core                | Figure 3                  |
Figure 1. Almaraz-II reactor core layout [15]

Figure 2. Almaraz II burnable poison rod arrangement within an assembly [15]
3. Methodology

The preparation of cross section data is very important in the use of core fuel management code [11-14]. The PWR-FUEL code requires cross sections in various reactor operating conditions. The cross section of materials Almaraz-II reactor is generated by the SRAC2006 code using PIJ cell calculations. The PIJ program uses the neutron transport method. The cross section is generated in 2 (two) groups of neutrons, fast and thermal. The cross section is generated for 6 (six) types of fuel assembly, namely:

a. Enrichment 2.1% without burnable poison
b. Enrichment 2.6% without burnable poison
c. Enrichment 3.1% without burnable poison
d. Enrichment 2.6% with 12 burnable poison
e. Enrichment 2.6% with 16 burnable poison
f. Enrichment 2.6% with 20 burnable poison

The cross section generation can be divided into two parts that the cross section in fresh condition and as a function of the fuel burnup. In fresh conditions, there are 5 operating conditions, whereas at the burn up conditions there are 15 steps of burn up for each type of fuel assembly to be generated from 0.0 GWd / tHM - 50 GWd / tHM. The selected operating conditions are:

a. Case A: $T_{fuel} = 20 \, ^\circ C$ ; $T_{cladding} = 20 \, ^\circ C$ and $T_{moderator} = 20 \, ^\circ C$
b. Case B: $T_{fuel} = 291.4 \, ^\circ C$; $T_{cladding} = 291.4 \, ^\circ C$ and $T_{moderator} = 291.4 \, ^\circ C$
c. Case C: $T_{fuel} = 704 \, ^\circ C$ ; $T_{cladding} = 340 \, ^\circ C$ and $T_{moderator} = 309.9 \, ^\circ C$
d. Case D: $T_{fuel} = 904 \, ^\circ C$ ; $T_{cladding} = 340 \, ^\circ C$ and $T_{moderator} = 309.9 \, ^\circ C$
e. Case E: \( T_{\text{fuel}} = 704 \, ^{\circ}\text{C} \); \( T_{\text{cladding}} = 340 \, ^{\circ}\text{C} \) and \( T_{\text{moderator}} = 279.9 \, ^{\circ}\text{C} \).

Operating conditions used for cross section generation as a function of burn up fraction using Case C (1000 ppm boron in moderator). For fresh condition, conducted at boron 0 ppm and 1000 ppm. The generated cross section accuracy is expressed in \( k_{\text{inf}} \) of each cell calculation. There are 5 (five) countries that participated in validation activity of Almaraz-2 cell calculation result such as Spain (SPA), India (IND), South Africa (SAP), Turkey (TUR) and Croatia (CRO).

Therefore, the accuracy of the results of the calculations of all institutions, including SRAC-2006, will be compared with the results of the Spanish (SPA). Fig 3. Almaraz II rod cluster control assembly pattern [15].

4. Results and discussion
Verification and validation computer code are basic calculation to know the accuracy and reliability of the calculation results. Table 2 presents the calculated cell \( k_{\text{inf}} \) value of SRAC2006 (PTKRN) for 6 types of non-boron fuel assembly (0 ppm) for each operating condition (T), compared with 5 other institutions.

| Fuel assembly 2.1% ppm | T | SPA | IND | SAP | TUR | CRO | PTKRN |
|------------------------|---|-----|-----|-----|-----|-----|-------|
| 0                      |   |     |     |     |     |     |   |
| A                      | 1.28558 | 1.29692 | 1.2875 | 1.28451 | 1.28805 | 1.29695 |
| B                      | 1.24877 | 1.26303 | 1.2505 | 1.24599 | 1.24984 | 1.25933 |
| C                      | 1.22941 | 1.24416 | 1.23194 | 1.22536 | 1.23193 | 1.23875 |
| D                      | 1.22279 | 1.23751 | 1.22479 | 1.21988 | 1.22641 | 1.23285 |
| E                      | 1.23841 | 1.2525 | 1.24062 | 1.23939 | 1.24178 | 1.24856 |

| Fuel assembly 2.6% ppm | T | SPA | IND | SAP | TUR | CRO | PTKRN |
|------------------------|---|-----|-----|-----|-----|-----|-------|
| 0                      |   |     |     |     |     |     |   |
| A                      | 1.34788 | 1.35929 | 1.35022 | 1.346 | 1.34916 | 1.35908 |
| B                      | 1.30594 | 1.32024 | 1.30743 | 1.3019 | 1.30532 | 1.31597 |
| C                      | 1.28513 | 1.30003 | 1.28762 | 1.27981 | 1.28594 | 1.29389 |
| D                      | 1.27829 | 1.29317 | 1.2806 | 1.27417 | 1.28025 | 1.28781 |
| E                      | 1.29562 | 1.30982 | 1.29755 | 1.29551 | 1.29745 | 1.30529 |

| Fuel assembly 3.1% ppm | T | SPA | IND | SAP | TUR | CRO | PTKRN |
|------------------------|---|-----|-----|-----|-----|-----|-------|
| 0                      |   |     |     |     |     |     |   |
| A                      | 1.39370 | 1.40536 | 1.39642 | 1.39108 | 1.39383 | 1.40479 |
| B                      | 1.34785 | 1.36244 | 1.34922 | 1.34273 | 1.34570 | 1.35746 |
| C                      | 1.32603 | 1.3413 | 1.32848 | 1.31962 | 1.32527 | 1.3343 |
| D                      | 1.31903 | 1.33434 | 1.32066 | 1.31390 | 1.31950 | 1.3281 |
| E                      | 1.33761 | 1.35216 | 1.33940 | 1.33655 | 1.33803 | 1.3468 |

| Fuel assembly 2.6% with 12 burnable poison ppm | T | SPA | IND | SAP | TUR | CRO | PTKRN |
|-----------------------------------------------|---|-----|-----|-----|-----|-----|-------|
| 0                      |   |     |     |     |     |     |   |
| A                      | 1.22020 | 1.22202 | 1.22315 | 1.20708 | 1.20511 | 1.21908 |
| B                      | 1.15389 | 1.15674 | 1.15439 | 1.1486 | 1.13413 | 1.1542 |
| C                      | 1.13261 | 1.13576 | 1.13409 | 1.12649 | 1.11450 | 1.13217 |
| D                      | 1.12638 | 1.12955 | 1.12715 | 1.12177 | 1.10926 | 1.12663 |
| E                      | 1.14575 | 1.14884 | 1.14695 | 1.14256 | 1.12826 | 1.14553 |
Fuel assembly 2.6% with 16 burnable poison

| ppm | T  | SPA   | IND   | SAP   | TUR   | CRO   | PTKRN |
|-----|----|-------|-------|-------|-------|-------|-------|
| 0   | A  | 1.17835 | 1.18324 | 1.18143 | 1.16374 | 1.15765 | 1.17870 |
| 0   | B  | 1.10748 | 1.11264 | 1.10772 | 1.09980 | 1.08247 | 1.10953 |
| 0   | C  | 1.08642 | 1.09214 | 1.08760 | 1.08004 | 1.06325 | 1.08767 |
| 0   | D  | 1.08039 | 1.08612 | 1.08089 | 1.07558 | 1.05817 | 1.08228 |
| 0   | E  | 1.09988 | 1.10579 | 1.10087 | 1.09605 | 1.07705 | 1.10135 |

Fuel assembly 2.6% with 20 burnable poison

| ppm | T  | SPA   | IND   | SAP   | TUR   | CRO   | PTKRN |
|-----|----|-------|-------|-------|-------|-------|-------|
| 0   | A  | 1.13789 | 1.14225 | 1.14090 | 1.12183 | 1.11232 | 1.13708 |
| 0   | B  | 1.06375 | 1.06768 | 1.06365 | 1.05495 | 1.03465 | 1.06483 |
| 0   | C  | 1.04300 | 1.04696 | 1.04381 | 1.03583 | 1.01588 | 1.04331 |
| 0   | D  | 1.03717 | 1.04114 | 1.03732 | 1.03162 | 1.01094 | 1.03809 |
| 0   | E  | 1.05661 | 1.06093 | 1.05733 | 1.05169 | 1.02956 | 1.05708 |

The accuracy of the results of the SRAC-2006 calculation can be seen in Figures 4-9, which shows the Δk results of each institution compared to the Spanish (SPA) as reference.

Figure 4. The value of Δk for each operating condition for fuel assembly 2.1%

Figure 5. The value of Δk for each operating condition for fuel assembly 2.6%
Figure 6. The value of $\Delta k$ for each operating condition for fuel assembly 3.1%

Figure 7. The value of $\Delta k$ for each operating condition for fuel assembly 2.6% with 12 burnable poison

Figure 8. The value of $\Delta k$ for each operating condition for fuel assembly 2.6% with 16 burnable poison
Figure 9. The value of Δk for each operating condition for fuel assembly 2.6% with 20 burnable poison

It is apparent in Figures 4-9 that the value of Δk of SRAC-2006 results is compared with Spanish results (SPA) in the range of -0.001 - 0.011. Large Δk values occur for Case A and fuel assembly without burnable poison, as shown in Figure 4-6. The value of Δk decreases, or in other words very close to the SPA results, for the case of fuel assembly that have burnable poison, as presented in Figures 7-9. This shows that the calculation of k_{inf} with SRAC-2006 has a good accuracy.

The difference in the value of Δk reaching 0.011 with the calculation of SRAC-2006 in the fuel assembly is consistent with the result of India (IND). Similar to that generated by SRAC-2006, IND calculation results the value of Δk also decrease using the fuel assembly with burnable poison calculation. However, calculations from TUR and CRO institutions produce the opposite result. The cause of this difference in value of Δk is not simple to explain, but one possible cause of the difference is in the nuclear data used, in addition to the neutron transport method used. In this study, the SRAC-2006 code uses ENDF / B-VII nuclear data.

The value of k_{inf} as show in Table 2, i.e. the results of cell calculation SRAC-2006, is consistent with the expected value that the largest occur in case A compared to 4 (four) other cases, i.e. in cold temperature (cold) has a higher value of k_{inf} compared to hot temperatures. Likewise, the k_{inf} value decrease with increase in number of burnable poison (pyrex) because of greater reaction of neutron absorption by boron. Table 3 presents the calculated k_{inf} value of PIJ calculation results (SRAC-2006), i.e. on the PTKRN column, for 5 (five) operating conditions, T, and 6 (six) types of fuel assembly compared to 5 (five) other institutions. The condition of boron in this condition is 1000 ppm.

| Table 3. k_{inf} values for each operating condition (T) and each fuel assembly |
|------------------------------------------|----------|----------|----------|----------|----------|
| Fuel assembly 2.1%                       |          |          |          |          |          |
| ppm | T | SPA | IND | SAP | TUR | CRO | PTKRN |
|-----|---|-----|-----|-----|-----|-----|-------|
| 1000 | A | 1.06973 | 1.07791 | 1.06694 | 1.07010 | 1.07723 | 1.07438 |
| 1000 | B | 1.08552 | 1.09911 | 1.08770 | 1.08621 | 1.09074 | 1.09276 |
| 1000 | C | 1.07630 | 1.09001 | 1.07868 | 1.07568 | 1.08219 | 1.08237 |
| 1000 | D | 1.07033 | 1.08414 | 1.07258 | 1.07089 | 1.07717 | 1.07717 |
| 1000 | E | 1.07268 | 1.08564 | 1.07553 | 1.07656 | 1.07971 | 1.07920 |

| Fuel assembly 2.1% 2.6%                  |          |          |          |          |          |
|------------------------------------------|----------|----------|----------|----------|----------|
| ppm | T | SPA | IND | SAP | TUR | CRO | PTKRN |
|-----|---|-----|-----|-----|-----|-----|-------|
| 1000 | A | 1.14592 | 1.15480 | 1.14353 | 1.14619 | 1.15282 | 1.15070 |
| 1000 | B | 1.15566 | 1.16982 | 1.15756 | 1.15545 | 1.15957 | 1.16264 |
The accuracy of the results of the SRAC-2006 calculation can be seen in Figure 10-15 which shows the magnitude of each institution compared to the Spanish (SPA result as references).
Figure 10. The value of each operating condition for the fuel assembly 2.1%

Figure 11. The value of each operating condition for the fuel assembly 2.6%

Figure 12. The value of each operating condition for the fuel assembly 3.1%
Figures 10-15 show that the value of $\Delta k$ of SRAC-2006 results is compared with Spanish results (SPA) in the range of $-0.005$ - $0.007$. The highest value of $\Delta k$ occur for case B for 2.1%, 2.6% and 3.1% enrichment, in addition to 2.1% and 2.6% in case D and E. Compared with other institutions, the maximum difference of 0.007 indicates the modeling has a good accuracy. This difference probably...
due to the nuclear data used is ENDF/B-VII which is much more recent than that of other institutions. Table 4 - 9 show the result of $k_{inf}$ value as a function of the fuel burnup for fuel assembly with enrichment of 2.1%, 3.1%, and 2.6% (without pyrex) and 2.6% with pyrex (12, 16 and 20).

Table 4. The value of $k_{inf}$ as a function of the fuel burnup (BU) for fuel assembly 2.1%

| BU, GWd/tHM | SPA | IND | CRO | SAF | TUR | SER | PTKRN |
|------------|-----|-----|-----|-----|-----|-----|-------|
| 0          | 1.07630 | 1.09001 | 1.08219 | 1.07868 | 1.07568 | 1.08720 | 1.08237 |
| 0.15       | 1.04163 | 1.05207 | 1.04930 | 1.04471 | 1.04062 | 1.05213 | 1.04588 |
| 2          | 1.03382 | 1.03866 | 1.03699 | 1.03307 | 1.02830 | 1.04420 | 1.03504 |
| 4          | 1.01710 | 1.02112 | 1.01828 | 1.01520 | 1.00988 | 1.01177 | 1.01809 |
| 6          | 0.99792 | 1.00130 | 0.99787 | 0.99586 | 0.99040 | 1.00794 | 0.99954 |
| 8          | 0.97898 | 0.98201 | 0.97798 | 0.97721 | 0.97195 | 0.98881 | 0.98156 |
| 10         | 0.96107 | 0.96438 | 0.95915 | 0.95960 | 0.95479 | 0.97072 | 0.96452 |
| 14         | 0.92807 | 0.93239 | 0.92507 | 0.92806 | 0.92378 | 0.93739 | 0.93337 |
| 18         | 0.89850 | 0.90410 | 0.89516 | 0.89558 | 0.89631 | 0.90752 | 0.90516 |
| 22         | 0.87191 | 0.87873 | 0.86877 | 0.87381 | 0.87168 | 0.88067 | 0.87971 |
| 26         | 0.84812 | 0.85602 | 0.84529 | 0.85059 | 0.84595 | 0.85664 | 0.85696 |
| 30         | 0.82704 | 0.83523 | 0.82436 | 0.82989 | 0.82972 | 0.83535 | 0.83688 |
| 34         | 0.80859 | 0.81657 | 0.80570 | 0.81163 | 0.81201 | 0.81671 | 0.81937 |
| 38         | 0.79263 | 0.79985 | 0.78913 | 0.79569 | 0.79627 | 0.80059 | 0.80429 |
| 42         | 0.77894 | 0.78483 | 0.77456 | 0.78189 | 0.78233 | 0.78676 | 0.79143 |
| 46         | 0.76728 | 0.77148 | 0.76189 | 0.77003 | 0.77002 | 0.77499 | 0.78052 |
| 50         | 0.75740 | 0.75953 | 0.75110 | 0.75986 | 0.75914 | 0.76501 | 0.77131 |

Table 5. The value of $k_{inf}$ as a function of the fuel burnup (BU) for fuel assembly 3.1%

| BU, GWd/tHM | SPA | IND | CRO | SAF | TUR | SER | PTKRN |
|------------|-----|-----|-----|-----|-----|-----|-------|
| 0          | 1.19641 | 1.21152 | 1.19971 | 1.19871 | 1.19399 | 1.20858 | 1.20195 |
| 0.15       | 1.15679 | 1.16830 | 1.16172 | 1.15959 | 1.15525 | 1.16851 | 1.16188 |
| 2          | 1.14043 | 1.14617 | 1.14084 | 1.13941 | 1.13474 | 1.15195 | 1.14190 |
| 4          | 1.12088 | 1.12434 | 1.11983 | 1.11873 | 1.11368 | 1.13220 | 1.12155 |
| 6          | 1.09967 | 1.10190 | 1.09800 | 1.09727 | 1.09194 | 1.11077 | 1.10048 |
| 8          | 1.07882 | 1.08064 | 1.07679 | 1.07655 | 1.07112 | 1.08971 | 1.08018 |
| 10         | 1.05900 | 1.06087 | 1.05659 | 1.05692 | 1.05154 | 1.06969 | 1.06093 |
| 14         | 1.02224 | 1.02456 | 1.01949 | 1.02124 | 1.01576 | 1.03256 | 1.02557 |
| 18         | 0.98869 | 0.99200 | 0.98605 | 0.98873 | 0.98367 | 0.99867 | 0.99319 |
| 22         | 0.95753 | 0.96218 | 0.95549 | 0.95855 | 0.95394 | 0.96720 | 0.96313 |
| 26         | 0.92835 | 0.93461 | 0.92723 | 0.93032 | 0.92632 | 0.93772 | 0.93511 |
| 30         | 0.90104 | 0.90855 | 0.90096 | 0.90388 | 0.90052 | 0.91014 | 0.90903 |
| 34         | 0.87566 | 0.88428 | 0.87649 | 0.87921 | 0.87644 | 0.88450 | 0.88494 |
| 38         | 0.85229 | 0.86160 | 0.85372 | 0.85634 | 0.85406 | 0.86090 | 0.86290 |
| 42         | 0.83101 | 0.84041 | 0.83268 | 0.83537 | 0.83338 | 0.83940 | 0.84296 |
| 46         | 0.81189 | 0.82081 | 0.81349 | 0.81635 | 0.81441 | 0.82009 | 0.82513 |
| 50         | 0.79495 | 0.80272 | 0.79629 | 0.79929 | 0.79714 | 0.80298 | 0.80934 |
Table 6. The value of $k_{ef}$ as a function of the fuel burnup (BU) for fuel assembly 2.6 %

| BU, GWd/tHM | SPA     | IND     | CRO     | SAF     | TUR     | SER     | PTKRN   |
|-------------|---------|---------|---------|---------|---------|---------|---------|
| 0           | 1.14454 | 1.15645 | 1.14910 | 1.14688 | 1.14295 | 1.12085 | 1.15032 |
| 0.15        | 1.01664 | 1.11758 | 1.11293 | 1.10958 | 1.10550 | 1.16851 | 1.11148 |
| 2           | 1.09312 | 1.09921 | 1.09496 | 1.09222 | 1.08767 | 1.15195 | 1.09456 |
| 4           | 1.07418 | 1.07779 | 1.07742 | 1.07216 | 1.06711 | 1.13220 | 1.07508 |
| 6           | 1.05353 | 1.05576 | 1.05276 | 1.05115 | 1.04581 | 1.11077 | 1.05462 |
| 8           | 1.03292 | 1.03497 | 1.03174 | 1.03091 | 1.02558 | 1.08971 | 1.03492 |
| 10          | 1.01358 | 1.01583 | 1.01178 | 1.01182 | 1.00688 | 1.06969 | 1.01629 |
| 14          | 0.97787 | 0.98090 | 0.97541 | 0.97732 | 0.97238 | 1.03256 | 0.98219 |
| 18          | 0.94547 | 0.94978 | 0.94289 | 0.94602 | 0.94150 | 0.99867 | 0.95109 |
| 22          | 0.91568 | 0.92143 | 0.91356 | 0.91721 | 0.91360 | 0.96720 | 0.92254 |
| 26          | 0.88832 | 0.89556 | 0.88692 | 0.89069 | 0.88797 | 0.93772 | 0.89636 |
| 30          | 0.86331 | 0.87146 | 0.86254 | 0.86632 | 0.86446 | 0.91014 | 0.87253 |
| 34          | 0.84068 | 0.84939 | 0.84025 | 0.84414 | 0.84295 | 0.88450 | 0.85108 |
| 38          | 0.82044 | 0.82916 | 0.81998 | 0.82417 | 0.82341 | 0.86090 | 0.83200 |
| 42          | 0.80259 | 0.81064 | 0.80168 | 0.80639 | 0.80575 | 0.83940 | 0.81523 |
| 46          | 0.78703 | 0.79389 | 0.78543 | 0.79071 | 0.78989 | 0.82099 | 0.80067 |
| 50          | 0.77360 | 0.77873 | 0.77124 | 0.77701 | 0.77574 | 0.80298 | 0.78809 |

Table 7. The value of $k_{ef}$ as a function of the fuel burnup (BU) for fuel assembly 2.6% (12 Pyrex)

| BU, GWd/tHM | SPA     | IND     | CRO     | SAF     | TUR     | SER     | PTKRN   |
|-------------|---------|---------|---------|---------|---------|---------|---------|
| 0           | 1.02775 | 1.03157 | 1.01460 | 1.02900 | 1.02084 | 1.03941 | 1.02612 |
| 0.15        | 0.99856 | 1.00022 | 0.98871 | 1.00032 | 0.99242 | 1.00985 | 0.99578 |
| 2           | 1.06064 | 1.00499 | 0.99745 | 1.00476 | 0.99705 | 1.01738 | 1.00127 |
| 4           | 1.00733 | 1.00824 | 1.00018 | 1.00452 | 0.99736 | 1.01808 | 1.00249 |
| 6           | 1.00331 | 1.00536 | 0.99791 | 1.00095 | 0.99424 | 1.01462 | 1.00040 |
| 8           | 0.99769 | 0.99920 | 0.99257 | 0.99542 | 0.98915 | 1.00893 | 0.99638 |
| 10          | 0.99020 | 0.99243 | 0.98480 | 0.98798 | 0.98210 | 1.00136 | 0.99033 |
| 14          | 0.96934 | 0.97247 | 0.96382 | 0.96804 | 0.96253 | 0.98026 | 0.97207 |
| 18          | 0.94371 | 0.94775 | 0.93899 | 0.94330 | 0.93829 | 0.95435 | 0.94828 |
| 22          | 0.91687 | 0.92201 | 0.91338 | 0.91740 | 0.91317 | 0.92720 | 0.92275 |
| 26          | 0.89106 | 0.89738 | 0.88875 | 0.89242 | 0.88905 | 0.90110 | 0.89795 |
| 30          | 0.86713 | 0.87417 | 0.86574 | 0.86915 | 0.86656 | 0.87690 | 0.87497 |
| 34          | 0.84534 | 0.85278 | 0.84455 | 0.84785 | 0.84587 | 0.85487 | 0.85416 |
| 38          | 0.82578 | 0.83310 | 0.82514 | 0.82861 | 0.82698 | 0.83509 | 0.83557 |
| 42          | 0.80842 | 0.81501 | 0.80759 | 0.81138 | 0.80983 | 0.81753 | 0.81917 |
| 46          | 0.79318 | 0.79858 | 0.79185 | 0.79611 | 0.79434 | 0.80212 | 0.80483 |
| 50          | 0.77994 | 0.78363 | 0.77806 | 0.78269 | 0.78041 | 0.78873 | 0.79240 |
Table 8. The value of $k_{inf}$ as a function of the fuel burnup (BU) for fuel assembly 2.6% (16 Pyrex)

| BU, GWd/tHM | SPA | IND | CRO | SAF | TUR | SER | PTKRN |
|------------|-----|-----|-----|-----|-----|-----|-------|
| 0          | 0.99118 | 0.97322 | 0.97322 | 0.98404 | 1.00283 | 0.99103 |
| 0.15       | 0.96461 | 0.95040 | 0.92602 | 0.95801 | 0.97590 | 0.96292 |
| 2          | 0.97865 | 0.97198 | 0.96744 | 0.97732 | 0.96935 | 0.99007 | 0.97420 |
| 4          | 0.98548 | 0.98723 | 0.97742 | 0.98327 | 0.97581 | 0.99698 | 0.98080 |
| 6          | 0.98745 | 0.98948 | 0.98115 | 0.98510 | 0.97801 | 0.99897 | 0.98358 |
| 8          | 0.98640 | 0.98742 | 0.98058 | 0.98409 | 0.97737 | 0.99791 | 0.98387 |
| 10         | 0.98254 | 0.98435 | 0.97651 | 0.98019 | 0.97385 | 0.99401 | 0.98147 |
| 12         | 0.96626 | 0.96925 | 0.96020 | 0.96467 | 0.95869 | 0.97754 | 0.96821 |
| 14         | 0.94275 | 0.94684 | 0.93769 | 0.94200 | 0.93666 | 0.95375 | 0.94700 |
| 16         | 0.92167 | 0.92208 | 0.91325 | 0.91703 | 0.91255 | 0.92757 | 0.92262 |
| 18         | 0.89158 | 0.89791 | 0.89227 | 0.89257 | 0.88989 | 0.90198 | 0.89838 |
| 20         | 0.86801 | 0.87501 | 0.86675 | 0.86967 | 0.86689 | 0.87814 | 0.87573 |
| 22         | 0.84650 | 0.85385 | 0.84590 | 0.84867 | 0.84651 | 0.85638 | 0.85516 |
| 24         | 0.82716 | 0.83436 | 0.82683 | 0.82967 | 0.82788 | 0.83681 | 0.83676 |
| 26         | 0.80996 | 0.81643 | 0.80952 | 0.81264 | 0.81092 | 0.81941 | 0.82050 |
| 28         | 0.79484 | 0.80012 | 0.79399 | 0.79752 | 0.79559 | 0.80412 | 0.80627 |
| 30         | 0.78167 | 0.78525 | 0.78032 | 0.78419 | 0.78178 | 0.79079 | 0.79390 |

The calculation results show that the maximum value $k_{inf}$ ($\Delta k$) occurs at 50 GWd/tHM for fuel assembly 2.6% without pyrex with 1000 ppm with difference 1.87%.

5. Conclusions
The cross section generation fuel assembly of the Almaraz-II reactor has been completed with the SRAC2006 code. Cross section data for various operating conditions are available so that it can be used for PWR-FUEL program validation. The difference in maximum $k_{inf}$ value with a reference value of 1.87% indicates that the cross section generation obtained has high accuracy.
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