BATAN-2DIFF AND -3DIFF DIFFUSION CODES VALIDATION ON KYOTO UNIVERSITY CRITICAL ASSEMBLY (KUCA)

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ABSTRACT

BATAN-2DIFF AND -3DIFF DIFFUSION CODES VALIDATION ON KYOTO UNIVERSITY CRITICAL ASSEMBLY (KUCA). Validation of Batan's standard multidimensional, multigroup diffusion code, Batan-2DIFF and -3DIFF, on the C-type cores (uranium fueled and water moderated) of the Kyoto University Critical Assembly (KUCA) have been successfully conducted. Three kinds of fuel assemblies of different pitch dimensions, i.e. C30, C35 and C45 were used to assemble ten core configurations (three, four, and three core configurations used C30, C35 and C45 fuel assemblies, respectively). Four neutron energy group cross section sets for the diffusion calculations were generated by WIMS/D4 cell calculation code. For all core configurations considered, the $k_{eff}$ values calculated by Batan-2DIFF and -3DIFF codes with WIMS/D4 library were very close to the experimental values and had maximum deviation from the experimental $k_{eff}$ of 2.65 % and 2.38 %, respectively, which proved the validation of the codes.

INTRODUCTION

One objective of the research activities in the Center for Multipurpose Reactor, for the first five years of the Second Long Range Development Plan (1994-1999) is the capability of National Atomic Energy Agency (Batan) to self-develop standard code systems required for neutronic and thermal-hydraulic designs as well as safety analyses of critical assemblies, research and power reactors.

In the first phase of the efforts to meet the objective, the completion of Batan standard codes for neutron diffusion was considered to be of the highest priority. Batan-1DIFF [1], -2DIFF [2] and -3DIFF [3] neutron diffusion codes have been successfully developed and compiled, and they join the line-up of Batan's standard codes. These Batan's standard diffusion codes have certain features which are not available in other generic diffusion codes, i.e. treatment of the $(n,2n)$ neutron scattering, directional diffusion constants, power peaking factor calculation based on the edge mesh flux, and special treatment for control rod worth calculations.

To verify the calculation results of Batan-2DIFF and -3DIFF codes, other generic diffusion codes, i.e. 2DBUM [4] and 3DBUM [5] codes, have been extensively used. The verification results showed excellent agreements in the effective multiplication factors, group neutron flux and power density.

* Center for Multipurpose Reactor - BATAN
distributions, local and global neutron balances, and other important parameters for reactor design and analyses. These codes are now being used in reactor design practices in the Agency. Several encouraging suggestions for improving the codes have arisen. One of the suggestions is to verify the codes not only to other generic diffusion codes but also with the experimental results [6].

This report deals with the validation results of Batan-2DIFF and -3DIFF codes with experimental results obtained from the Kyoto University Critical Assembly (KUCA), Japan. A critical assembly has been chosen since it provides advantageous conditions for code validation. A critical assembly is usually configured to be very close to critical (negligible excess reactivity) condition, and it operates in a zero-power mode so that the assembly has a uniform temperature distribution and problems related to core cooling, xenon poisoning, temperature and power reactivity effects, severe distortion on the neutron flux distribution attributed to high neutron absorption of control rods can be easily avoided [7]. These advantageous conditions are expected to remove undesirable effects which may degrade the validation results of the present work.

The validation works have twofold objectives. Besides validation of Batan-2DIFF and -3DIFF codes, the WIMS/D4 cell calculation code [8] can also be simultaneously verified. Although this 1-D cell calculation code has been widely used and verified by other foreign institutions, the present work will also contribute in providing comprehensive verification results of the combination between Batan-2DIFF or -3DIFF and WIMS/D4 codes. On top of that, the capability of the two-dimensional diffusion code, Batan-2DIFF, to treat 3-D critical assembly geometry will also be investigated. A proper treatment of the axial neutron leakage with buckling correction obtained with least square procedure is proposed.

CODE VALIDATION PROCEDURE

The validation procedure of Batan-2DIFF and -3DIFF codes is shown in Fig.1 and will be explained in detail in the following subsections. First, brief description of the KUCA is presented. Secondly, the neutronic modeling for the 1-D cell calculation with WIMS/D4 code will be discussed. The third part of this section will discuss the validation procedure through diffusion calculations with Batan-2DIFF and -3DIFF codes. The last part deals with the critical experiment of KUCA to obtain the effective multiplication factors.
Description of Kyoto University Critical Assembly

KUCA constructed in 1974 at Kumatori, Osaka Prefecture, is one of the seven critical assembly facilities in Japan. KUCA has three types of core loading (namely A, B, and C cores) designed for various reactor physics studies and for educational purposes. Among the three cores, the A and B cores use solid moderator while the C core is light-water moderated. For the present work, only C core was used and so it will be elaborated below in detail.

The C core consists of several fuel assemblies surrounded by light water reflector. Three types of fuel assembly based on their pitch dimension (distance between fuel plates) are available, namely C45, C35 and C30, which have 4.5, 3.5 and 3.0 mm pitch dimensions, respectively. The first criticality experiments utilizing these three fuel assemblies were consecutively achieved in August and September, 1974; and the operation license was issued in February, 1975. Since then, various national and private institutions as well as universities conduct reactor physics experiments [9].

The water-moderated C core of the KUCA is immersed in a water tank with 1.8 m depth and 2 m diameter. The core is equipped with three safety rods and three control rods. Neutron multiplication can be controlled by the control rods and/or water level. Corresponding to the C30, C35 and C45 fuel assemblies mentioned above, three types of aluminium side plates are used with different grooves, that is, 2.96 mm, 3.49 mm and 4.54 mm pitches, respectively. In assembling a fuel assembly with these side plates, one can insert up to 31, 40 and 47 fuel plates, respectively, over the full 140 mm length of the element. Therefore, a fuel assembly can be filled with full number of fuel plates or just part of them. Figs. 2 and 3 show the fuel assembly of KUCA and the aluminium side plate of fuel assembly, respectively.

Each fuel plate contains uranium-aluminium alloy meat (specific gravity 3.22, enrichment 93.10 w/o) of 0.5 mm thickness, cladded on both sides by 0.5 mm thick aluminium layer. Fig. 4 shows a fuel plate of KUCA. A typical fuel plate contains 8.89 g 235U. Thus, the H/235U atomic ratios for a homogenized fuel region including the two side plates are 159, 212 and 315 for the three pitch spacing dimensions C30, C35 and C45, respectively. The fuel assemblies are erected to a grid plate in the tank where the grid pitches are 71 mm by 142 mm.

Ten core configurations were used for Batan-2DIFF and -3DIFF codes validation. The core configurations are divided into three groups, i.e. three of C30, four of C35 and three of C45 core configurations. Only three representative core configurations for each group are shown in Figs. 5, 6, and 7, for C30, C35 and C45 fuel assemblies, respectively. For example, the C45G0(4 rows) is a core configuration where C45 denotes the core loaded with
C45 fuel assemblies, G0 a water gap between the grid plate is 0 cm, and 4 rows means the configuration consists of four rows fuel assemblies in X- or Y-axis direction.

Cell Calculations

For diffusion group constant generation, WIMS/D4 1-D cell calculation code based on multigroup neutron transport theory was used. The real 3-D fuel assembly geometry must be approximated with 1-D equivalent cell. For axial direction of the fuel assembly the material composition is almost uniform so that this direction can be neglected. Observing the cross-sectional figure of the fuel assembly the transversal direction of the fuel assembly must be chosen for the 1-D equivalent cell model. Other parts of the fuel assembly, such as side plates, which can not be included in the 1-D equivalent cell model is taken into account in the extra region, one option provided by WIMS/D4 code.

The multiplate option was chosen for modeling this 1-D cell and the group constants were condensed into four energy groups. The fast energy region is collapsed into 3 groups, i.e. 10 MeV to 821 keV, 821 keV to 5.53 keV and 5.53 keV to 0.625 eV, and the thermal energy region is collapsed into a single group, i.e. 0.625 eV - 0 eV. Buckling correction option was also activated in the cell calculation to approximate the real core spectrum to be used in the condensation. Fig. 8 shows the 1-D cell model for C-35 fuel assembly with its full number of fuel plates. As commonly known, for non-fuel region, such as light water reflector, a special technique for picking out group constants set from WIMS/D4 was used.

Diffusion Calculations

The full core diffusion calculations in 2-D X-Y reactor geometry and 3-D X-Y-Z reactor geometry using the group constant set from WIMS/D4 were conducted for the selected ten core configurations explained previously. Batan-2DIFF and -3DIFF codes used in the diffusion calculations solve the following eigenvalue problem of the multigroup neutron diffusion:

\[
M\Phi = \frac{1}{k_{\text{eff}}} F\Phi,
\]

with \(M\) and \(F\) denotes the neutron migration & loss operator and fission source operator.
\[ M\Phi = -\nabla \cdot D_x(r) \nabla \phi_g(r) + \Sigma_{r,k}(r) \phi_g(r) \]
\[ - \sum_{g' \neq g} \Sigma_{g',g} \phi_{g'}(r), \]
\[ F\Phi = \chi_g \sum_{g' = 1}^G \nu \Sigma_{f,g} \phi_{g'}(r). \]  

Notation \( k_{\text{eff}} \) is the effective multiplication factor which is the eigenvalue of Eq.(1). Other notations are commonly used in the reactor physics textbooks and will not be explained further.

As already discussed in the cell calculation method, the core material composition in the axial direction is nearly homogeneous. Therefore, for 2-D calculations by Batan-2DIFF code, the 3-D reactor geometry can be treated accurately with a 2-D \( X-Y \) reactor geometry using a proper correction of axial neutron leakage. Considering the uniform distribution of the core material the axial buckling correction in the absorption cross section is commonly used to approximate the axial neutron leakage [10].

\[ \Sigma_{a,k}(r) = \Sigma_{r,k}(r) + D_x(r) B_{z,k}^2(r). \]  

The axial buckling denoted with \( B_{z,k} \) may be energy group, position or material dependent. Now, the axial buckling must be estimated to simulate accurately the axial neutron leakage. Diffusion calculations in 2-D \( R-Z \) reactor geometry will be used to determine the axial buckling through the axial group neutron flux distributions. The typical core-reflector configuration for the \( R-Z \) geometry is shown in Fig.9. In these calculations, the 3-D reactor geometry is approximated with a 2-D cylindrical geometry where volumes of each material in the 3-D geometry are conserved in the 2-D \( R-Z \) calculations. Then, the axial group neutron flux distribution at the center of the reactor is fitted by a least square method [11] to a cosine distribution,

\[ \phi_g(z) = A \cos (B_{z,k} z), \]

where \( A \) and \( B_{z,k} \) are parameters to be determined with least square procedure, and \( z \) is the distance from the centre/middle height of the core. A small program to do the least square fitting has been developed for the present work. Using this method, only 2-D diffusion calculations are involved so that all calculations can be done only with Batan-2DIFF code. The axial bucklings obtained from the 2-D \( R-Z \) geometry are then to be used for diffusion calculations in the 2-D \( X-Y \) reactor geometry.

In case of Batan-3DIFF code, the diffusion calculations can be done
without approximation in the reactor geometry, i.e. the 3-D X-Y-Z geometry can be applied directly.

The calculation results of Batan-2DIFF and -3DIFF in terms of the effective multiplication factor are then compared to the measured value obtained from the criticality experiments. In order to justify the accuracy of Batan-2DIFF and -3DIFF codes, effective multiplication factors calculated with (a) KENO V.a code [12] based on Monte Carlo method using two types of nuclear libraries, i.e. the Hansen Roach Library [13] and the MGCL [14], and (b) CITATION code [15] in 3-D X-Y-Z reactor geometry using group constant set prepared with the SRAC code system [16], are also presented. The group constant sets used by the CITATION code were generated with SRAC code system, therefore, comparisons between the WIMS/D4 and SRAC cell calculation codes can also be conducted. The calculation results using the KENO V.a and CITATION codes were taken from Ref.17.

**Criticality Experiment**

The procedure to achieve a critical state of a core configuration consists of five main steps:

**Step 1. Initial Loading**

Firstly, before conducting initial loading of fuel assembly, the water in the tank is dumped out, and the neutron source is inserted in the prescribed position. Then, all safety rods are fully withdrawn. Secondly, the fuel assembly is assembled in the tank and the tank is filled with water.

**Step 2. Measurement**

The inverse count rates are measured for three combinations of control rod positions and plotted to predict the critical fuel plate number. The three combinations are (1) all control rods fully inserted, (2) one control rod is fully inserted and the other two are fully withdrawn, and (3) all control rods are fully withdrawn. During this step, criticality state may be achieved and the procedure continues to Step 5. If criticality is not achieved then before adding more fuel plates according to the predicted critical number of fuel plate the critical assembly must be shut-down.

**Step 3. Shutdown**

The critical assembly is shut-down by first withdrawing the neutron source, followed by inserting all (three) control rods and finally dumping the water out of the tank.
Step 4. Addition of fuel plates

A number of fuel plates is added in the fuel assembly and the procedure is continued to Step 2, 3 and 4 until criticality is achieved.

Step 5. Calibration of control rods.

A control rod might be partially inserted when the critical state is achieved. The inserted part of the control rod is then calibrated to obtain the true multiplication factor of the critical assembly.

VALIDATION RESULTS & DISCUSSION

Firstly, the results of the diffusion calculation in 2-D $R-Z$ reactor geometry with Batan-2DIFF code for the ten core configurations are discussed. After each eigenvalue diffusion calculation, the axial group neutron flux distribution at the center of the reactor was extracted. Fig. 9 shows the axial group neutron flux distributions at the center of the assembly for C30G0 (3 rows) core configuration. Except at the core-reflector boundaries, the group neutron flux distributions resemble a cosine profile which supports our argument that if the axial material composition of core is uniform then the axial neutron leakage can be properly approximated with axial buckling corrections.

These axial group neutron flux distributions were then fitted using least square procedure to obtain the group dependent axial buckling values, and the results are tabulated in Table 1. It can be observed from the table that the bucklings of the three fuel assemblies showed consistent behavior in that an assembly with a higher moderation ratios have also higher buckling values. Higher buckling values indicate neutrons born in the core will leak out of the core easier since the fissile nuclide densities are lower. Furthermore, from the same table it can be observed that for a particular core or assembly, the buckling values decrease as the neutron energy decreases. This is attributed to less neutron absorption at higher neutron energy since in general the absorption cross section of the fuel decreases as the neutron energy increases.

Secondly, utilizing the axial buckling obtained from the previous 2-D $R-Z$ diffusion calculations, diffusion calculations in 2-D $X-Y$ reactor geometry were conducted and the results are summarized in Table 2. In the table, besides the effective multiplication factors calculated with Batan-2DIFF code, values calculated with Batan-3DIFF, KENO V.a and CITATION codes are compared with the measured/experimental values. In general, all codes produced effective multiplication factors very close to the values obtained from criticality experiments. For the ten core configurations, the maximum deviation of the effective multiplication factor from the experimental values
were about 8.57 % and 3.07 % for the Monte Carlo KENO V.a code with Hansen Roach and MGCL libraries, respectively. On the other hand, the maximum deviation for Batan-2DIFF and -3DIFF (WIMS/D4 library), CITATION (3-D) code (SRAC library) were 2.65 %, 2.38 % and 2.10 %, respectively. Although, theoretically KENO V.a code would produce better results, the results of the Monte Carlo simulation with Hansen Roach library deviated greater than the diffusion theory did. Furthermore, the CITATION (3-D) combined with group constant set generated by SRAC gave slightly overestimated values of $k_{eff}$ while Batan-2DIFF and -3DIFF with WIMS/D4 produce slightly underestimated values of $k_{eff}$.

CONCLUDING REMARKS

Validation of Batan's standard 2-D and 3-D multigroup diffusion codes, Batan-2DIFF and 3-DIFF, on the C-type cores (uranium fueled and water moderated) of the Kyoto University Critical Assembly (KUCA) have been conducted. Three kinds of fuel assemblies with different fuel plate pitch dimensions, i.e. C30, C35 and C45 were used to assemble ten core configurations (three, four, and three core configurations used C30, C35 and C45 fuel assemblies, respectively). Four group cross section sets for diffusion calculation were generated with WIMS/D4 cell calculation code. For 2-D calculations with Batan-2DIFF code the group dependent axial bucklings were determined by fitting the axial neutron flux distributions (obtained from the 2-D R-Z diffusion calculations) with least square procedure. Then, the axial bucklings were used in the 2-D X-Y diffusion calculations to take into account the axial neutron leakage. The effective multiplication factors calculated were compared to the experimental values and calculated values by KENO V.a Monte Carlo code (3-D, Hansen Roach and MGCL libraries) and CITATION code (3-D, SRAC library). For all core configurations considered, the effective multiplication factors calculated by Batan-2DIFF and -3DIFF codes were very close to the experimental values. The maximum deviation from the experimental values calculated by Batan-2DIFF and -3DIFF were around 2.65 % and 2.38 %, respectively, which proved the validation of the codes.

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of completing the present work. The authors wish to express their deep appreciation to Dr. Amin Santosa Zarkasi for his valuable discussion and critical advices. The data manipulation and graphs were carefully prepared by Mr. Asnul Sufmawan.

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Tabel I. Group dependent, axial buckling values obtained from 2-D $R-Z$ diffusion calculations with Batan-2DIFF code.

<table>
<thead>
<tr>
<th>Core</th>
<th>Axial Squared Buckling, $B^2_{z,r} \times 10^{-3} \text{ cm}^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Group 1</td>
</tr>
<tr>
<td>C30G0(3 rows)</td>
<td>1.7311</td>
</tr>
<tr>
<td>C30G0(4 rows)</td>
<td>1.7504</td>
</tr>
<tr>
<td>C30G0(5 rows)</td>
<td>1.7518</td>
</tr>
<tr>
<td>C35G0(3 rows)</td>
<td>1.8051</td>
</tr>
<tr>
<td>C35G0(4 rows)</td>
<td>1.8220</td>
</tr>
<tr>
<td>C35G0(5 rows)</td>
<td>1.8229</td>
</tr>
<tr>
<td>C35G0(6 rows)</td>
<td>1.8232</td>
</tr>
<tr>
<td>C45G0(3 rows)</td>
<td>1.8735</td>
</tr>
<tr>
<td>C45G0(4 rows)</td>
<td>1.8936</td>
</tr>
<tr>
<td>C45G0(5 rows)</td>
<td>1.8950</td>
</tr>
</tbody>
</table>
Table 2. Comparison of the $k_{eff}$ from the experimental data, and calculated values with KENO V.a, CITATION, Batan-2DIFF and -3DIFF codes.

<table>
<thead>
<tr>
<th>Core</th>
<th>Experimental $k_{eff}$</th>
<th>Batan-2DIFF</th>
<th>Batan-3DIFF</th>
<th>CITATION (3-D)</th>
<th>KENO V.a (3-D)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>WIMS/D4 Library</td>
<td>WIMS/D4 Library</td>
<td>SRAC Library</td>
<td>Hansen Roach Library</td>
</tr>
<tr>
<td>C45G0(3 rows)</td>
<td>1.0009</td>
<td>0.9904 (0.9895)</td>
<td>0.9967 (0.9958)</td>
<td>1.0044 (1.0035)</td>
<td>1.0370 (1.0360)</td>
</tr>
<tr>
<td>C45G0(4 rows)</td>
<td>1.0011</td>
<td>0.9746 (0.9735)</td>
<td>0.9773 (0.9762)</td>
<td>1.0058 (1.0047)</td>
<td>1.0381 (1.0370)</td>
</tr>
<tr>
<td>C45G0(5 rows)</td>
<td>1.0008</td>
<td>0.9955 (0.9947)</td>
<td>0.9991 (0.9983)</td>
<td>0.9933 (0.9925)</td>
<td>1.0866 (1.0857)</td>
</tr>
<tr>
<td>C35G0(3 rows)</td>
<td>1.0002</td>
<td>0.9850 (0.9848)</td>
<td>0.9905 (0.9903)</td>
<td>0.9991 (0.9989)</td>
<td>1.0467 (1.0465)</td>
</tr>
<tr>
<td>C35G0(4 rows)</td>
<td>1.0018</td>
<td>0.9834 (0.9816)</td>
<td>0.9877 (0.9859)</td>
<td>0.9986 (0.9968)</td>
<td>1.0502 (1.0483)</td>
</tr>
<tr>
<td>C35G0(5 rows)</td>
<td>1.0011</td>
<td>0.9948 (0.9937)</td>
<td>0.9989 (0.9978)</td>
<td>1.0039 (1.0028)</td>
<td>1.0001 (0.9990)</td>
</tr>
<tr>
<td>C35G0(6 rows)</td>
<td>1.0003</td>
<td>0.9870 (0.9867)</td>
<td>0.9908 (0.9905)</td>
<td>1.0058 (1.0055)</td>
<td>1.0272 (1.0269)</td>
</tr>
<tr>
<td>C30G0(3 rows)</td>
<td>1.0002</td>
<td>0.9901 (0.9899)</td>
<td>0.9962 (0.9960)</td>
<td>1.0212 (1.0210)</td>
<td>1.0411 (1.0409)</td>
</tr>
<tr>
<td>C30G0(4 rows)</td>
<td>1.0010</td>
<td>0.9812 (0.9802)</td>
<td>0.9834 (0.9824)</td>
<td>1.0101 (1.0090)</td>
<td>1.0563 (1.0552)</td>
</tr>
<tr>
<td>C30G0(5 rows)</td>
<td>1.0008</td>
<td>0.9968 (0.9960)</td>
<td>0.9982 (0.9974)</td>
<td>1.0077 (1.0069)</td>
<td>1.0570 (1.0561)</td>
</tr>
</tbody>
</table>
PRESENT WORK

Figure 1. Flowchart of Batan-2DIFF and -3DIFF codes validation on KUCA.
Figure 2. Fuel assembly of KUCA.

<table>
<thead>
<tr>
<th></th>
<th>C45</th>
<th>C35</th>
<th>C30</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.05mm</td>
<td>1.095mm</td>
<td>1.07mm</td>
</tr>
<tr>
<td>B</td>
<td>2.84mm</td>
<td>1.79mm</td>
<td>1.26mm</td>
</tr>
<tr>
<td>C</td>
<td>4.54mm</td>
<td>3.49mm</td>
<td>2.96mm</td>
</tr>
</tbody>
</table>

Number of pitch

Figure 3. Aluminium side plate of fuel assembly.
$U^{235} : 8.89 \text{ g/m}^2/\text{plate}$
$U : 9.55 \text{ g/m}^2/\text{plate}$
Enrichment : 93.10% Uranium : 20wt% in U-Al alloy

Figure 4. Fuel plate of KUCA.

Figure 5. C30G0 (5 rows) core configuration.
Figure 6. C35G0(3 rows) core configuration.

Figure 7. C45G0(4 rows) core configuration.
Figure 8. 1-D cell model for C35 fuel assembly (40 plates).

Figure 9. Core configuration for R-Z calculation.
Figure 10. Axial group neutron flux distribution for C30G0(3 rows).