Analysis on the KUCA MEU Experiments (I)

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ABSTRACT

In accordance with the joint ANL-KURRI program, the critical experiments using MEU fuel in the KUCA, a light-water-moderated and
heavy-water-reflected single-core, were started in May, 1981. Thereafter, the KUCA experiments have been providing useful data with
regard to the RERTR program.

This paper provides some results on the analysis of the following KUCA critical experiments: (1) the critical approaches for HEU and MEU
single-cores and (2) the reactivity effect measurements of boron
burnable-poison for MEU cores. Five-group constants were generated
using the EPRI-CELL code, and two-dimensional diffusion calculations
were performed using a current finite-difference code [DIF3D(2D)] and a
finite-element code [2D-FEM-KUR]. Some of the results from the two
diffusion codes were compared with each other. Taking advantage of the
finite-element method, the 2D-FEM-KUR code was applied to a detailed
analysis of the experiments measuring the burnable-poison effects.

Differences between the results of calculations and experiments
were less than 1.8% in the C/E ratios for the eigenvalues. The
agreement between the results obtained using the DIF3D(2D) code and the
2D-FEM-KUR code was excellent. The measurements of the burnable-poison
effects were approximately simulated by the calculations using the
2D-FEM-KUR code.

INTRODUCTION
A joint ANL-KURRI [Argonne National Laboratory - Kyoto University Research Reactor Institute] program \(^{1}\) was initiated in 1978 for reducing the enrichment of the fuel to be used in the KUHFR [Kyoto University High Flux Reactor] \(^{2}\). A distinct feature of the KUHFR is that it has a coupled-core configuration. The core consists of two annular modules that are light-water moderated and placed within a heavy-water reflector with a specified distance between them. The Phase A reports of the joint ANL-KURRI program, independently prepared by ANL and KURRI in February 1979, concluded that MEU [Medium Enriched Uranium] fuel is feasible for the KUHFR. \(^3\), \(^4\)

In accordance with the ANL-KURRI joint study concerning the RERTR [Reduced Enrichment for Research and Test Reactors] program, the critical experiments using MEU fuel in the KUCA [Kyoto University Critical Assembly] \(^5\) were started in May, 1981. Thereafter, the KUCA experiments have been providing useful data with regard to the RERTR program. \(^6\), \(^7\), \(^8\), \(^9\), \(^10\)

This paper provides some results of the analysis on the KUCA critical experiments using the ANL code system. \(^11\), \(^12\) These include: (1) the critical approaches for HEU [Highly Enriched Uranium] and MEU cores and (2) the reactivity effect measurements of boron burnable-poison [BP] for MEU cores. The ANL code system employed in this study consists of two codes: (1) the EPRI-CELL code \(^13\) for the generation of group constants and (2) the DIF3D code \(^14\) for diffusion calculations. Since the ANL code system was employed in the earlier neutronics calculations for the KUHFR, it is important to assess its capabilities for the KUHFR type core. The KUHFR has a unique core configuration which is difficult to model precisely with current diffusion theory codes based on the finite-difference method. The KUCA core employed in this series of critical experiments was similar to that of the KUHFR, although it was a single-core and not a coupled-core. Even for this simpler KUCA core, it is still difficult to model the geometry precisely with a finite-difference diffusion code such as the DIF3D code.

This paper also provides some results from a finite-element diffusion code [2D-FEM-KURR] \(^15\), \(^16\), which was developed in a cooperative research program between KURRI and JAERI [Japan Atomic Energy Research Institute]. This code provides the capability for mocking-up a complex
core configuration such as that of the KUHFR. Using the same group constants generated by the EPRI-CELL code, the 2D-FEM-KUR code was applied to the analysis of the KUCA experiments. Some of the results from the 2D-FEM-KUR code were compared with the DIF3D code. Taking advantage of the finite-element method, the 2D-FEM-KUR code was applied to a detailed analysis of the experiments measuring the BP effects.

EXPERIMENTAL

1. KUCA Fuel Assemblies

The specifications of the HEU and MEU fuel plates are tabulated in Tables 1-1 and 1-2. An illustration of the fuel plate and side-plates is shown in Fig. 1. The HEU fuel plates were fabricated in Japan by Nuclear Fuel Industries [NFI], and the MEU fuel plates were fabricated in France by Compagnie pour l'Etude et la Realisation de Combustibles Atomiques [CERCA]. One by one, each curved fuel plate was inserted between two aluminum side-plates until a complete fuel element was formed. For the MEU fuels, special side-plates containing boron BP were also fabricated by CERCA (see Fig. 1).

Figure 2 shows a heavy-water tank which is employed in the KUCA single-core experiments as a container for the heavy-water reflector. Figure 3 shows a view of the assembled fuel elements. This assembly is then installed in the center of the heavy-water tank and filled with light-water to form a light-water-moderated, heavy-water-reflected core. The core has a cylindrical center island of light-water, and the fuel region is divided into two parts by the space for the control rods. The inner fuel region consists of 6 fuel elements which are numbered as IN-01, IN-02, etc. The outer fuel region consists of 12 elements numbered as OUT-01, OUT-02, etc. The maximum number of fuel plates which can be loaded in a fuel element is 15 plates per element for an inner fuel element and 17 plates per element for an outer fuel element.

A typical core configuration is shown in Fig. 4. The criticality of the core was controlled by three rods, namely C1, C2 and C3 rods, because all safety rods were withdrawn to their upper limit at every operation. The detectors were arranged around the heavy-water tank, and the neutron source was located under the heavy-water tank.
2. Critical Approach

As a first step for the critical approach of the core, all outer fuel elements were fully loaded with 17 fuel plates (204 fuel plates total). Next, the critical approach was performed by inserting fuel plates into the inner fuel elements from the outside towards the inside in order. At that time, all side-plates contained no BP. The inverse multiplication method was adopted for the critical approach. The detectors used in this experiment were the three fission chambers utilized for the start-up channels, namely #1, #2 and #3.

The first critical state of the MEU single-core was achieved with 262 fuel plates. The masses of $^{235}$U and U were 4165.74g and 9284g, respectively. The excess reactivities measured by the positive period method were 0.211%Δk/k for the core with a 3.84mm fuel pitch and 0.077%Δk/k for the core with a 3.80mm fuel pitch.

On the other hand, the critical state of the HEU single-core was formerly achieved with 276 fuel plates. The masses of $^{235}$U and U were 3524.46g and 3784g, respectively. The excess reactivity was 0.468%Δk/k for the core with a 3.84mm fuel pitch.

3. Reactivity Effects of Boron Burnable-Poison [BP]

Reactivity effects of the side-plates containing boron BP were measured in the following manner: substituting a fuel element with BP for an element without BP one by one, the excess reactivity or subcriticality of the core was measured before and after the substitution. The excess reactivity was measured by the positive period method, and the subcriticality was measured by the source multiplication method. The reactivity effect of the BP side-plates was obtained from the difference between the reactivities measured before and after each substitution.

In each measurement, the objective fuel element for the substitution was filled to its capacity with fuel plates. For the measurements of the BP reactivity effect in the outer fuel region, all outer fuel elements were loaded with 17 fuel plates. For the BP effect measurements in the inner fuel region, all inner fuel elements were loaded with 15 fuel plates.

The criticality of the core was adjusted by the number of fuel plates loaded in the core. For the BP effect measurements in the outer
fuel region, the criticality was adjusted by the number of fuel plates inserted in the inner part of the inner fuel elements. On the other hand, for the measurements in the inner fuel region, the criticality was adjusted by the number of fuel plates inserted in the outer part of the outer fuel elements. Therefore, the mass reactivity effects of the fuel plates were also obtained.

In the measurements of BP effects, the fuel pitch in the fuel element with BP was 3.80mm, and that in the element without BP was 3.84mm. The use of side-plates containing BP is attempted in the KUHFR to suppress the excess reactivity of the initial core loaded with fresh fuel and to obtain a longer fuel life.

Due to the interference effects between side-plates containing BP, the measured reactivity effect for each substitution was not constant. The reactivity effects for the substitution were approximately $-0.4\%\Delta k/k$ per outer fuel element and $-0.6\%\Delta k/k$ per inner element. The total reactivity effects of BP were approximately $-4.7\%\Delta k/k$ in the outer fuel region when there was no BP in the inner fuel region, and $-3.7\%\Delta k/k$ in the inner fuel region when there was no BP in the outer fuel region. Taking into account the interference effect between the inner and outer side-plates with BP, the total reactivity effect of BP in the core would be approximately $-8\%\Delta k/k$.

**CALCULATIONS**

1. Description of the Codes

Microscopic broad-group cross-sections were generated using the EPRI-CELL code. This code combines a heterogeneous Pl GAM\textsuperscript{17} type treatment for the fast and resonance ranges and a heterogeneous integral-transport treatment [THERMOS]\textsuperscript{18} for the thermal range. The Pl GAM type treatment includes (1) an interpolation over tabulated groupwise-resonance integrals as a function of temperature and potential scattering for the resonance self-shielding, (2) resonance overlap corrections, (3) an optional buckling search, and (4) many other refinements. The code also provides a cell depletion calculation using the CINDER code for each THERMOS space point in a depletable zone. Cell-averaged cross-sections at any preselected time in a depletion
history can be obtained in either a 2-, 3-, 4- or 5-group structure. A flow diagram of the EPRI-CELL code is shown in Fig. 5.

The EPRI-CELL libraries are mostly based on ENDF/B-IV data. The 68 group fast library is generated using MC2-19) and the integral transport RABANL option can be used for the resonance self-shielding parameters. The 35-group thermal library is generated using the AMPX20) or NJOY codes with an $S_{\alpha,s}$ treatment for hydrogen and deuterium.

The diffusion calculations were performed using the DIF3D and 2D-FEM-KUR codes. The DIF3D code has the capability for one- through three-dimensional diffusion calculations for several geometries based on the current finite-difference method. In this study, a two-dimensional option of the code [DIF3D(2D)] was adopted. The 2D-FEM-KUR code is a two-dimensional diffusion code based on the finite-element method.

2. Generation of Group Constants

The single-core employed in the KUCA critical experiments was divided into 10 regions for the MEU core and into 11 regions for the HEU core. For the MEU core, these regions are: (1) the inner and (2) the outer fuel regions, (3) the inner and (4) the outer side-plate regions, (5) the light-water region at the center of core, (6) the control rod region, (7) the outer vessel region between the outer fuel elements and the heavy-water reflector, (8) the heavy-water reflector region, (9) the outer wall region of the aluminum heavy-water tank, and (10) the light-water reflector region outside the heavy-water tank. For the HEU core, the inner vessel (11) which separates the inner fuel elements from the center island containing light-water was also modeled.

For generating the group constants, the EPRI-CELL code with a slab geometry was used for each of the above regions. The upper energy boundaries of the five-group structure used in this study were: 10MeV, 0.821MeV, 5.53keV, 1.855eV and 0.625eV.

For the inner (1) and outer (2) fuel regions shown in Fig. 6, the materials between two side-plates were modeled as a unit cell using a slab geometry for a fully loaded fuel element. The fuel meat, aluminum clad and light-water moderator were modeled preserving their thicknesses as shown in Fig. 6. The effect of a residual region between two side-plates, excluding the area within the dotted lines, was taken...
into account by using an extra region. RABANL corrections were applied for the resonance self-shielding.

For the inner (3) and outer (4) side-plate regions shown in Fig. 7, the treatment of the side-plates with and without boron BP was different. In each case, the small portion of light-water in the grooves for fuel plate insertion in the side-plates was ignored, but the light-water in a gap between two adjoining side-plates was taken into account. For the side-plates with BP, the spectrum for collapsing the cross-sections was generated using a homogenized core source. For the side-plates without BP, a simple $^{235}$U fission spectrum was assumed. For the side-plates with BP, all regions were represented preserving their thicknesses as shown in Fig. 7. The effect of end sections of the side-plates containing no BP were taken into account by using an extra region.

For regions (5) through (11), a $^{235}$U fission spectrum was employed for collapsing the cross-sections. In the control rod region (6), aluminum spacers, aluminum sheaths for the control rod insertion and all other aluminum support structures were homogenized. The inner (11) and the outer (7) vessel regions consist of aluminum and light-water. In these regions, heterogeneities were taken into account. For the outer tank wall region (9), the group constants prepared for aluminum in the outer vessel region (7) were utilized. For the center light-water (5) and the light-water reflector (10) regions, group constants were generated using a $^{235}$U fission spectrum for light-water of the same thickness.

3. Diffusion Calculations

In the Phase B calculations $^{21}$ for the KUHFR, axial reflector savings were derived by fitting axial flux distributions from an R-Z computation to a cosine curve. These varied by region from $\sim 10$cm in the center to $>15$cm in the heavy-water reflector. On the other hand, the experimental results gave the axial reflector savings as $8.1 \pm 0.1$cm in the center light-water region, $7.8 \pm 0.1$cm in the outer fuel region and $9.8 \pm 0.3$cm in the heavy-water reflector region, respectively. $^8$ In this study, the experimental values of the axial reflector savings were
adopted to calculate the transverse buckling employed in the two-dimensional diffusion calculations.

In the DIF3D(2D) code, one quarter of the core was modeled in X-Y geometry as shown in Fig. 8. In the inner part of the core, a mesh of approximately 0.25x0.25cm was employed. In the heavy-water reflector and in the heavy-water tank regions, a 1x1cm mesh was used. In the light-water reflector region, a 2x2cm mesh was used.

Figure 9 shows the core configuration simulated by the 2D-FEM-KUR code for the comparison with the DIF3D(2D) code. For the detailed analysis on the BP effect measurements, the full core was explicitly modeled by the 2D-FEM-KUR code as shown in Fig. 10, taking advantage of the finite-element method. Figure 11 shows an example of the finite-elements used in the detailed analysis on the BP effect measurements.

RESULTS AND DISCUSSIONS

Results of the calculations are tabulated in Tables 2 through 4 together with the experimental results. Table 2 shows a comparison between the DIF3D(2D) and 2D-FEM-KUR codes for the critical approach. Table 3 makes the same comparison for the BP effect measurements. Table 4 shows the results from the 2D-FEM-KUR code for the detailed analysis on the BP effect measurements. Figure 12 shows the reactivity effect caused by the substitution of a fuel element with BP for a fuel element without BP in the outer fuel region, and Fig. 13 shows the same for the inner fuel region.

Tables 2 through 4 show that ratios between the results of calculations and experiments (C/E ratios) are less than 1.8% for eigenvalues. The calculated eigenvalues are always higher than the experimental values. One reason for this tendency is due to the unit cell model employed for the fuel region in generating the group constants. In this study, an extra region was employed as shown in Fig. 6 so that the effect of the area surrounding an essential unit cell is taken into account. The extra region which consists of light-water and aluminum tends to increase the apparent H/235U ratio in the unit cell. This causes a shift from an under-moderated fuel region to a more moderated region and leads to the over-estimation of the eigenvalue.
Tables 2 and 3 show that the agreement between the results obtained using the DIF3D(2D) code and the 2D-FEM-KUR code was excellent. Both the 2D-FEM-KUR code with its explicit geometrical representation and the DIF3D(2D) code with a jagged X-Y approximation for the core can be used for neutronics design calculations of the KUHFR.

Table 4 shows that C/E ratios are less than 12% for BP reactivity effects and less than 13% for mass reactivity effects of the fuel plate. However, the agreement between the calculation and experiment was quite good for the total BP reactivity effect in the outer fuel region. Additionally, the agreement for the total mass reactivity effect in the outer fuel region was good considering the difficulty to calculate such effects based on diffusion theory. Figures 12 and 13 show that the calculation approximately reproduces the dependence observed in the experiments of the BP substitution effect upon the substituting position. However, for the inner fuel elements, calculations lead to the underestimation of the BP substitution effects by around 12%. On the other hand, for the outer elements, the BP substitution effects are approximately predicted except for a few substitutions.

While not yet satisfied with the results of these calculations, confidence has been gained through this study that the 2D-FEM-KUR code is an excellent tool for the analysis of the KUCA MEU experiments. The next step will be to use the SRAC code system for the generation of the group constants, since the SRAC code has a capability of a two-dimensional treatment for the generation of group constants.

ACKNOWLEDGEMENTS

This study was performed as a part of the joint ANL-KURRI program. The calculations using the ANL code system were performed at the Computer Center of ANL, and the calculations using the 2D-FEM-KUR code were mainly performed at the Data Processing Center of Kyoto Univ.

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to the members of the KUCA Technical Committee including Prof. Hiroshi Nishihara of Kyoto Univ., Prof. K. Nishina of Nagoya Univ., Dr. K. Tsuchihashi and Dr. S. Matsuura of JAERI for invaluable discussions.

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REFERENCES

Table 1-1. Specification of HEU fuel plates.

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Enrichment = 93.14%, Design pitch = 3.84 mm.

Table 1-2. Specification of MEU fuel plates.

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Enrichment = 44.07%, Design pitch = 3.00 mm.
Table 2. Eigenvalues for the critical state without burnable-poison (BP).
--- Comparison between the DIF3D(2D) and 2D-PFM-KUR codes ---

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Table 3. Boron burnable-poison (BP) effects for the MEU single-core.
--- Comparison between the DIF3D(2D) and 2D-PFM-KUR codes ---

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<th>* 2D-PFM-KUR *</th>
<th>Pitch (mm)</th>
<th>Number of plates</th>
<th>Eigenvalue</th>
<th>Reactivity effect of BP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Kexp</td>
<td>Kcal</td>
<td>C/E</td>
</tr>
<tr>
<td>Inner SP without BP</td>
<td>3.84 288</td>
<td>1.0047</td>
<td>1.0190</td>
<td>1.0142</td>
</tr>
<tr>
<td>Outer SP with BP</td>
<td>3.80 288</td>
<td>1.0047</td>
<td>1.0190</td>
<td>1.0142</td>
</tr>
<tr>
<td>All SP without BP</td>
<td>3.84 288</td>
<td>1.0047</td>
<td>1.0190</td>
<td>1.0142</td>
</tr>
<tr>
<td>All SP with BP</td>
<td>3.80 294</td>
<td>0.984</td>
<td>0.9940</td>
<td>1.010</td>
</tr>
<tr>
<td>All SP without BP</td>
<td>3.84 294</td>
<td>0.984</td>
<td>0.9940</td>
<td>1.010</td>
</tr>
</tbody>
</table>

SP : side-plate, * : estimated from experiments.
Table 4. Substitution effects of side-plates containing boron burnable-poison (BP) for the HEU single-core. -- Calculated by the 2D-FEM-KUR code --

<table>
<thead>
<tr>
<th>No. of Plates</th>
<th>No. of Elements with BP</th>
<th>Eigenvalue</th>
<th>Kexp</th>
<th>Kcal</th>
<th>C/E</th>
<th>BP Effect (%Δk/k)</th>
<th>Mass Effect** (%Δk/k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>263</td>
<td>0</td>
<td>1.0047</td>
<td>1.0143</td>
<td>1.0096</td>
<td>-0.44</td>
<td>-0.39</td>
<td>0.88</td>
</tr>
<tr>
<td>263</td>
<td>0</td>
<td>1.0004</td>
<td>1.0101</td>
<td>1.0100</td>
<td>-0.36</td>
<td>-0.39</td>
<td>1.07</td>
</tr>
<tr>
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<td>1.0064</td>
<td>1.0099</td>
<td>-0.37</td>
<td>-0.38</td>
<td>1.02</td>
</tr>
<tr>
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<td>1.0008</td>
<td>1.0110</td>
<td>1.0102</td>
<td>-0.37</td>
<td>-0.38</td>
<td>1.04</td>
</tr>
<tr>
<td>267</td>
<td>0</td>
<td>0.9969</td>
<td>1.0072</td>
<td>1.0103</td>
<td>-0.37</td>
<td>-0.38</td>
<td>1.04</td>
</tr>
<tr>
<td>267</td>
<td>0</td>
<td>1.0010</td>
<td>1.0114</td>
<td>1.0103</td>
<td>-0.37</td>
<td>-0.38</td>
<td>1.04</td>
</tr>
<tr>
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<td>-0.38</td>
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<tr>
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<td>1.0125</td>
<td>1.0110</td>
<td>0.36</td>
<td>0.38</td>
<td>1.06</td>
</tr>
<tr>
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<td>1.0164</td>
<td>1.0112</td>
<td>0.41</td>
<td>0.39</td>
<td>0.96</td>
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<tr>
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<td>1.0052</td>
<td>1.0169</td>
<td>1.0116</td>
<td>0.41</td>
<td>0.44</td>
<td>1.06</td>
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<tr>
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<td>1.0127</td>
<td>1.0118</td>
<td>0.36</td>
<td>0.33</td>
<td>0.92</td>
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<tr>
<td>277</td>
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<td>1.0045</td>
<td>1.0161</td>
<td>1.0115</td>
<td>-0.42</td>
<td>0.42</td>
<td>1.02</td>
</tr>
<tr>
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<td>1.0003</td>
<td>1.0118</td>
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<tr>
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<td>1.0177</td>
<td>1.0118</td>
<td>-0.41</td>
<td>-0.43</td>
<td>1.03</td>
</tr>
<tr>
<td>280</td>
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<td>1.0118</td>
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<td>0.38</td>
<td>1.03</td>
</tr>
<tr>
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<td>1.0161</td>
<td>1.0113</td>
<td>-0.34</td>
<td>-0.37</td>
<td>1.09</td>
</tr>
<tr>
<td>286</td>
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<td>1.0013</td>
<td>1.0123</td>
<td>1.0110</td>
<td>-0.34</td>
<td>-0.37</td>
<td>1.09</td>
</tr>
</tbody>
</table>

| total         | -4.74                  | -4.80      | 1.01  | 4.44  | 4.60  | 1.04 |

258           | 0                      | 1.0084     | 1.0238 | 1.0153 | -0.68 | -0.60 | 0.88 |
| 258           | 1                      | 1.0016     | 1.0176 | 1.0160 | 0.61  | 0.55  | 0.91 |
| 262           | 0                      | 1.0077     | 1.0233 | 1.0155 | -0.66 | -0.56 | 0.88 |
| 262           | 2                      | 1.0013     | 1.0175 | 1.0162 | 0.61  | 0.47  | 0.93 |
| 266           | 2                      | 1.0074     | 1.0233 | 1.0159 | -0.63 | -0.56 | 0.89 |
| 266           | 3                      | 1.0011     | 1.0177 | 1.0165 | 0.60  | 0.57  | 0.96 |
| 270           | 3                      | 1.0072     | 1.0239 | 1.0166 | -0.62 | -0.55 | 0.88 |
| 270           | 4                      | 1.0009     | 1.0179 | 1.0170 | 0.63  | 0.57  | 0.91 |
| 274           | 0                      | 1.0073     | 1.0239 | 1.0165 | -0.61 | -0.53 | 0.88 |
| 274           | 5                      | 1.0011     | 1.0183 | 1.0172 | 0.48  | 0.42  | 0.89 |
| 277           | 5                      | 1.0059     | 1.0228 | 1.0167 | -0.53 | -0.48 | 0.90 |
| 277           | 6                      | 1.0006     | 1.0178 | 1.0172 | -0.53 | -0.48 | 0.90 |

** : Fuel pitch is 3.80mm in the side-plate with BP and that is 3.84mm in the side-plate without BP. ** : Mass reactivity effect of the fuel plates.
(a) Fuel plate (the specification is tabulated in Table 1),
(b) Side-plate with 3.84 mm pitch (without burnable-poison):
   inner fuel element: \( L = 59.34 \text{ mm}, E_1 = 1.75 \text{ mm}, E_0 = 2.08 \text{ mm} \),
   outer fuel element: \( L = 67.41 \text{ mm}, E_1 = 2.10 \text{ mm}, E_0 = 2.12 \text{ mm} \),
(c) Side-plate with 3.80 mm pitch (with burnable-poison):
   inner fuel element: \( L = 59.40 \text{ mm}, L_s = 48 \text{ mm}, 10B = 104 \text{ mg} \),
   outer fuel element: \( L = 67.00 \text{ mm}, L_s = 55 \text{ mm}, 10B = 117 \text{ mg} \),
(d) Side-plate with 3.80 mm pitch (without burnable-poison):
   inner fuel element: \( L = 59.40 \text{ mm} \),
   outer fuel element: \( L = 67.00 \text{ mm} \).

Fig. 1 Illustration of the fuel plate and side-plates.
Fig. 2 View of the aluminum heavy-water tank for a single-core.

Fig. 3 View of the assembled fuel elements for a MEU or HEU core.
Fig. 4  Typical core configuration employed in the KUCA MEU experiments.
Fig. 5 Flow diagram of the EPRI-CELL code.
Fig. 6 Model for the fuel region used in an unit cell calculation.
Fig. 7 Model for the side-plate region with boron burnable-poison used in a cell calculation.
Fig. 8 Example of a jagged X-Y approximation for a quarter of a HEU single-core used in the DIF3D(2D) code.

Fig. 9 Example of an explicit representation for a quarter of a HEU single-core used in the 2D-FEM-KUR code for a comparison with the DIF3D(2D) code.
Fig. 10 Example of an explicit representation of a full MEU single-core used in the 2D-FEM-KUR code for a detailed analysis on the burnable-poison [BP] effect measurements.

Fig. 11 Example of finite-elements used in the 2D-FEM-KUR code.
Fig. 12 Reactivity effects caused by the substitution of the outer fuel element with boron burnable-poison [BP] for the outer element without BP.

Fig. 13 Reactivity effects caused by the substitution of the inner fuel element with BP for the outer element without BP.