TWO-DIMENSIONAL FULL-CORE TRANSPORT THEORY BENCHMARKS FOR THE WWER REACTORS

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ABSTRACT

Several two-dimensional full-core real geometry many-group steady-state problems for the WWER-440 and WWER-1000 reactors have been solved by the MARIKO code, based on the method of characteristics. The reference transport theory solutions include assembly-wise and pin-wise power distributions. Homogenized two-group diffusion parameters and discontinuity factors have been calculated by MARIKO for each assembly type both for the whole assembly and for each cell in the smallest sector of symmetry, using the B1 method for calculation of the critical spectrum. Accurate albedo-type boundary conditions have been calculated by MARIKO for the core-reflector and core-absorber boundaries, both for each outer assembly face and for each outer cell face. Comparison with the reference solutions of the two-group nodal diffusion code SPPS-1.6 and the few-group fine-mesh diffusion codes HEX2DA and HEX2DB are presented.

1 Introduction

The two-dimensional full-core heterogeneous transport theory benchmarks have essential advantages compared to the diffusion theory benchmarks and the real experiments. Compared to the diffusion theory benchmarks they are more real, because they provide solution to the exact neutron transport equation for the real heterogeneous geometry. Compared to the real experiments their advantages are in the absence of experimental errors and uncertainties both in the geometry and material composition. The transport theory benchmarks are in fact ideal experiments.

The current paper presents four benchmarks for the WWER-440 reactor and one for the WWER-1000 reactor. All four WWER-440 benchmarks are for normal operating conditions. Ben440-1 is for the beginning of the first cycle with fresh fuel assemblies of the three standard fuel enrichments (1.6%, 2.4%, and 3.6%) and boron concentration typical for the beginning of a cycle. Ben440-2 is for the end of the first cycle conditions, with the same fuel assemblies as in Ben440-1, but depleted to about 10 MWD/kg and with zero boron concentration. Ben440-3 is representative for the beginning of the next cycles with fuel assemblies of the same initial enrichment (3.6%), but fresh, depleted to about 10 and 20 Mwd/kg with high boron concentration. Ben440-4 is the same as Ben440-3, except that the control group 6 is fully inserted. Thus nearly all essentially different cases are included.

The only benchmark for WWER-1000 (Ben1000-1) is for cold zero power conditions. It corresponds to experiments carried out at the V-1000 facility at the Kurchatov institute.

All reference solutions are obtained by solving two-dimensional full-core problems with exact geometry description of the fuel assemblies (Figures 1,2), the real radial reflector and absorber. Each material (fuel, cladding, coolant, ...) in each cell for each assembly type is characterized by 23-group transport cross sections, calculated by Helios[1] (with the 90-group library). Appropriate 23-group cross sections are prepared also for the reflector and absorber materials.

Using the 23-group transport cross sections, reference solutions have been calculated by the transport code Mariko[2, 3] with P_1-scattering accounted for. A 30-degree sector of the core is calculated for WWER-440 and a 60-degree sector for WWER-1000. The solution is obtained by solving three consecutive problems gradually increasing the number of polar levels, azimuthal angles and spatial tracks. The final solution is for 3 polar levels, 60 azimuthal angles and track separation of 0.05 cm for WWER-440 and 0.1 cm for WWER-1000. The same final solution is used to calculate radial boundary conditions—accurate transport theory 2-group (group to group) albedoes for each outer assembly face and also for each cell side on each outer assembly face. The same type of boundary conditions are calculated for the WWER-440 absorber, using the conventional supercell, corresponding to the control rod's pitch in the core. The reference solutions consist of assembly-wise and pin-wise power distributions.

Using the same 23-group transport cross sections, the same Mariko code in the same mode (the same angular and spatial discretization, P_1-scattering), two-group diffusion parameters and assembly-discontinuity factors have been calculated for each assembly type. These, together with the boundary conditions on the core-reflector and core-absorber boundary constitute the benchmark problems for a nodal diffusion code. Two-group diffusion parameters are calculated also for each cell for each assembly type. These, together with the cell side-averaged albedoes on the core-reflector and the core-absorber boundary constitute the benchmark problems for a fine-mesh diffusion code. The conventional B_1-method is applied to calculate the criticality spectrum for the homogenized assembly, which is used to condense all 2-group parameters. The B_1-method is also used to correct the diffusion coefficients.

It should be noted, that all 2-group diffusion parameters can be calculated by Helios, but

Helios solves the transport equation with the transport corrected cross sections, while Mariko uses P_1-scattering data (Mariko cannot use transport corrected cross sections for core-reflector problems, because of instability of the method of transmission probabilities, applied to accelerate the convergence). Using Mariko both for the calculation of the reference solution and for generation of the two-group diffusion parameters permits to separate the error introduced by the two-group diffusion approximation and the mathematical model (also its implementation) of the diffusion code.

2 Benchmarking SPPS-1.6

The SPPS-1.6 code[4] has been used for operational steady state neutronics calculations of the WWER-440 reactors at Kozloduy NPP since 1996. It is a two-group three-dimensional nodal diffusion code, its mathematical model based on the modal representation of the fluxes within each node.

The SPPS-1.6 solution for Ben440-1 (beginning of first cycle conditions) is compared to the reference solution on Fig. 3. The error in k_{eff} is only 29 pcm. The errors in the relative assembly powers in the core interior are surprisingly small. Obviously, there is a problem on the core-reflector boundary, most probably concerning the boundary conditions for the thermal group, but the RMS error is only 0.56%.

The errors for Ben440-2 (Fig. 4) are also very small—only -5 pcm in k_{eff} and the RMS error is 0.57%. A similar problem is observed on the core-reflector boundary.

Contrary to all expectations, the errors in the assembly-wise power distribution for Ben440-3 (Fig. 5) are greater that the errors for the first two benchmarks, although the spectrum differences between the assemblies are much smaller for Ben440-3. A possible explanation is an error compensation for the first two benchmarks. Again there is a problem on the core-reflector boundary, but the RMS error is only 0.78% and the error in k_{eff} is 2 pcm.

One would expect greater errors for Ben440-4, with control group 6 fully inserted (Fig. 6), but they are even smaller than for Ben440-3. In fact, the control group causes a small error compensation.

In general, except for the peripheral assemblies, the errors in the assembly-wise power distribution for the WWER-440 benchmarks are less than 1%, the RMS error is less than 1% too.

The comparison of SPPS-1.6 and Mariko results for Ben1000-1 is presented on Fig. 7. Now the error in k_{eff} is 243 pcm and the maximum relative error in the assembly-wise power distribution is 7.8% for the central assembly. Probably, the errors would have been smaller if it was a normal operating state. At room temperature without power feedbacks the WWER-1000 core is a severe problem for the diffusion codes, because the flux gradients inside the core are very big. On the other hand, the mathematical model of SPPS-1.6 is too simple for the WWER-1000 assemblies.

3 Benchmarking HEX2DA and HEX2DB

HEX2DA and HEX2DB are few-group two-dimensional fine-mesh diffusion codes, modeling the real cell structure of the WWER assemblies HEX2DA is a pure finite-difference code, which describes the inter-assembly gap by hexagonal cells, with the same approximation of the diffusion operator as in HEXAB2DB[5]. HEX2DB describes the inter assembly gap by pentagonal cells (each two/three adjacent pentagonal cells, belonging to the two/three adjacent assemblies are homogenized and treated as a single hexagonal cell in HEX2DA). Moreover,

HEX2DB has optional higher order approximation scheme for the diffusion operator, based on a second order polynomial approximation of the flux inside each cell with isotropic second derivative.

The results of HEX2DA and HEX2DB for the first three benchmarks are compared to the reference solutions on Figures 8-12. Both codes overestimate k_{eff}—HEX2DA by about 100 pcm and HEX2DB by about 200 pcm. The errors in the assembly-wise power distributions are almost the same for all three diffusion codes, they all underestimate the powers of the peripheral assemblies by 1-2.5%. All three diffusion codes have been tested by diffusion theory benchmarks and no such effect have been observed. This suggests the reason is in the diffusion approximation itself, not in the flux modeling in the diffusion codes. The two-group diffusion approximation is adequate inside the core, where the flux gradients are small, but leads to errors near the core-reflector boundary.

Ben440-4 has not been calculated by HEX2DA/B, because the internal boundary conditions, required to describe the control absorber, have not been implemented in the test versions of the codes.

The same underestimation of the powers of the peripheral assemblies is observed for Ben1000-1 (Figures 13, 14), but the errors are smaller, because the WWER-1000 assemblies are bigger. The relative error of the central assembly power is 3.0% for HEX2DA and -0.6% for HEX2DB. It must be noted that the more elaborate option in HEX2DB failed for this benchmark (because the pentagonal gap cells for this reactor are almost triangular) and the pure finite-difference option has been used. It is quite possible the very small errors of HEX2DB are due to error compensation.

The pin-wise power distribution by HEX2DB has been benchmarked[6] with the main conclusions that the errors for the internal assemblies are less than 2%, but big errors (up to 11%) have been observed for peripheral assemblies. The results in Ref. [6], however, were obtained with radial boundary conditions averaged over each outer assembly face. Becuase the radial reflector of the WWER-440 reactor is very complicated with big water regions, the albedoes vary significantly along an outer assembly face. The results on Fig. 15 for assembly 41 with the biggest errors in Ref. [6] have been obtained by using separate albedoes on each outer cell side. The maximum errors now are about 3% for the first three benchmarks.

4 Conclusions

Four two-dimensional full-core heterogeneous transport theory benchmarks have been presented for the WWER-440 reactors and one for the WWER-1000 reactor. The nodal diffusion code SPPS-1.6 and the fine-mesh diffusion codes HEX2DA and HEX2DB have been benchmarked. All three codes are adequate for the WWER-440 reactor, while SPPS-1.6 is not adequate for the WWER-1000 reactor. Errors of the diffusion approximation near the radial core-reflector boundary, resulting in relative errors of 1-2.5% in the powers of the peripheral assemblies have been detected. Therefore, transport theory correction have to be devised to eliminate the error.

References

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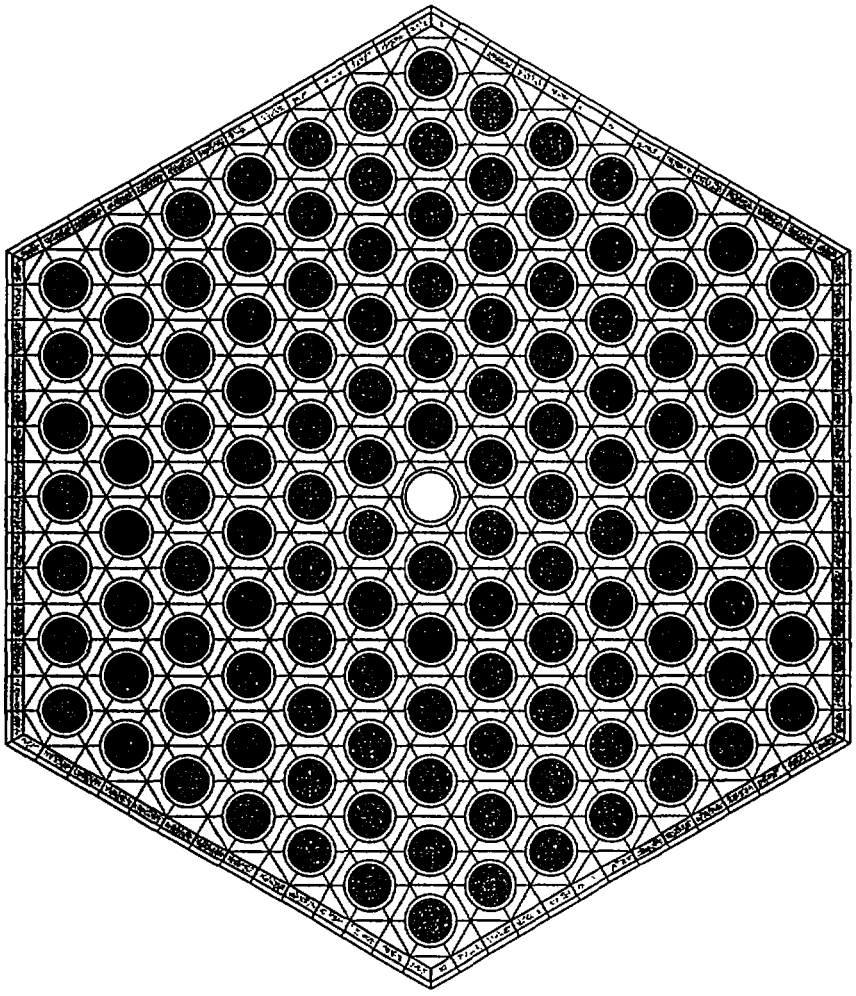

Figure 1: Geometry model of a WWER-440 assembly by MARIKO

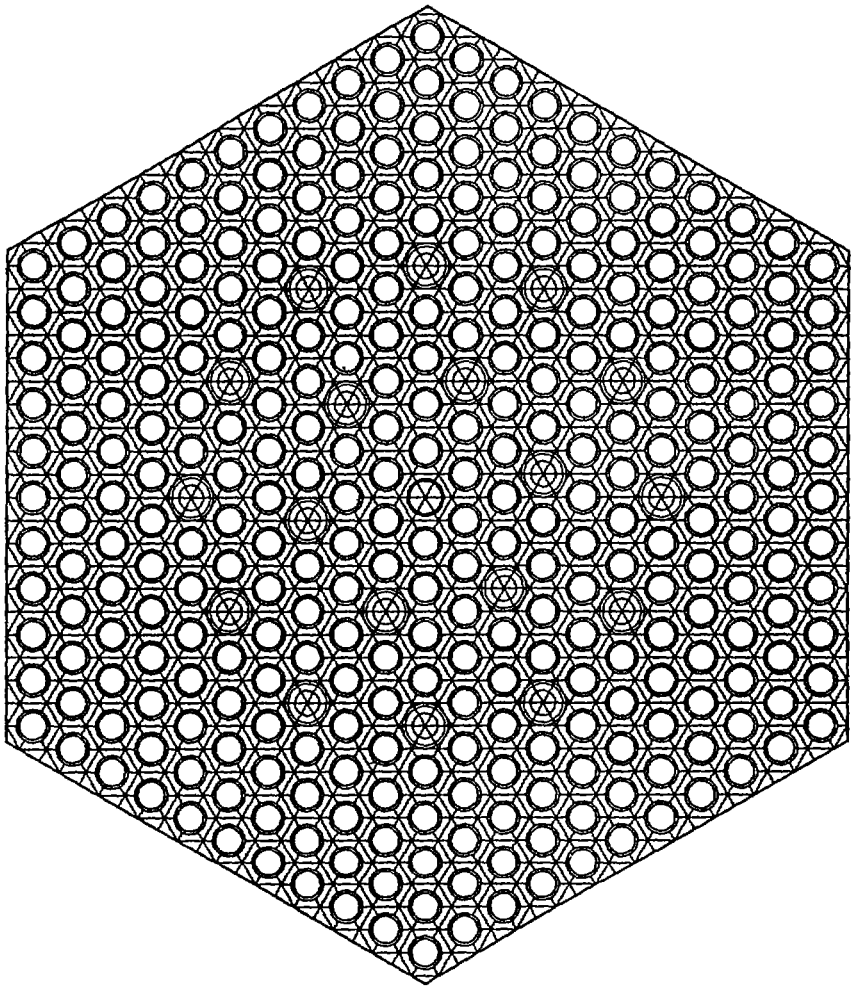

Figure 2: Geometry model of a WWER-1000 assembly by MARIKO

```
                                                    B/46  A/47
Power distribut. SPPS                              0.914 0.704
Relative error in %                                  0.3  -1.5
                                          B/38  B/39  A/40  A/41
RMS Error: 0.56%                         1.082 1.058 1.076 0.589
                                           0.2   0.3   0.2  -1.9
                                 B/30  C/31  C/32  C/33  A/34
                                1.101 0.869 0.876 0.840 0.956
                                  0.1   0.2   0.2   0.2  -0.4
                       B/21  C/22  C/23  B/24  B/25  A/26  A/27
                      1.188 0.916 0.899 1.134 1.140 1.264 0.813
                        0.1   0.0   0.1   0.2   0.4   0.2  -0.7
             B/11  C/12  B/13  B/14  B/15  C/16  C/17  A/18  A/19
            1.207 0.967 1.196 1.174 1.173 0.944 0.931 1.182 0.623
              0.1   0.0   0.1   0.1   0.2   0.1   0.2   0.2  -1.4
 B/01  C/02  B/03  B/04  C/05  C/06  B/07  B/08  A/09  B/10
1.168 0.947 1.213 1.218 0.956 0.948 1.196 1.203 1.369 0.782
  0.1   0.0   0.1   0.1   0.0   0.0   0.2   0.4   0.2  -0.4
```

Figure 3: Ben440-1: Comparison of SPPS-1.6 with Mariko (k_{eff}=0.99894, Err=29pcm)

```
                                                    B/46  A/47
Power distribut. SPPS                              0.720 0.521
Relative error in %                                 -0.1  -1.6
                                          B/38  B/39  A/40  A/41
RMS Error: 0.57%                         1.034 0.909 0.820 0.451
                                           0.2   0.0  -0.1  -1.7
                                 B/30  C/31  C/32  C/33  A/34
                                1.242 0.969 0.881 0.755 0.740
                                  0.3   0.2   0.0  -0.2  -0.6
                       B/21  C/22  C/23  B/24  B/25  A/26  A/27
                      1.452 1.151 1.062 1.147 1.032 0.995 0.635
                        0.4   0.2   0.1   0.2   0.1  -0.1  -0.6
             B/11  C/12  B/13  B/14  B/15  C/16  C/17  A/18  A/19
            1.557 1.293 1.445 1.349 1.247 0.969 0.851 0.895 0.483
              0.4   0.2   0.4   0.3   0.2  -0.1  -0.2  -0.2  -1.3
 B/01  C/02  B/03  B/04  C/05  C/06  B/07  B/08  A/09  B/10
1.560 1.330 1.551 1.502 1.205 1.120 1.212 1.094 1.079 0.610
  0.6   0.3   0.4   0.3   0.1   0.1   0.2   0.1  -0.2  -0.7
```

Figure 4: Ben440-2: Comparison of SPPS-1.6 with Mariko (k_{eff}=1.02380, Err=-5pcm)

```
                                                  B/46  A/47
Power distribut. SPPS                            0.829 0.594
Relative error in %                                0.4  -1.8
                                          B/38  B/39  A/40  A/41
RMS Error: 0.78%                         1.019 0.961 0.905 0.508
                                           0.2   0.2  -0.3  -2.2
                                 B/30  C/31  C/32  C/33  A/34
                                1.121 0.979 0.938 0.884 0.824
                                  0.2   0.5   0.5   0.5  -1.0
                       B/21  C/22  C/23  B/24  B/25  A/26  A/27
                      1.260 1.098 1.046 1.099 1.056 1.085 0.711
                        0.1   0.5   0.5   0.2   0.1  -0.5  -1.2
              B/11  C/12  B/13  B/14  B/15  C/16  C/17  A/18  A/19
             1.315 1.194 1.268 1.209 1.168 1.025 0.991 1.014 0.531
               0.2   0.5   0.2   0.1   0.2   0.4   0.4  -0.5  -2.0
 B/01  C/02  B/03  B/04  C/05  C/06  B/07  B/08  A/09  B/10
1.289 1.198 1.322 1.301 1.146 1.101 1.161 1.115 1.164 0.726
  0.2   0.5   0.2   0.1   0.5   0.5   0.1   0.1  -0.6  -0.4
```

Figure 5: Ben440-3: Comparison of SPPS-1.6 with Mariko (k_{eff}=1.01261, Err=2pcm)

```
                                                  B/46  A/47
Power distribut. SPPS                            1.067 0.782
Relative error in %                                0.6  -1.6
                                          B/38  B/39  A/40  A/41
RMS Error: 0.73%                         1.177 1.176 1.149 0.655
                                           0.3   0.4   0.0  -2.0
                                 B/30  C/31  C/32  C/33  A/34
                                1.157 1.044 1.049 1.043 1.007
                                  0.2   0.6   0.6   0.6  -0.8
                       B/21  C/22  C/23  B/24  B/25  A/26  A/27
                      1.279 1.107 1.017 1.056 1.092 1.220 0.833
                        0.2   0.5   0.5   0.3   0.1  -0.3  -1.1
              B/11  C/12  B/13  B/14  B/15  C/16  C/17  A/18  A/19
             1.178 1.177 1.264 1.113 0.863 0.769 0.969 1.113 0.609
               0.2   0.5   0.2   0.3   0.1   0.0   0.5  -0.4  -1.9
 B/01  C/02  B/03  B/04  C/05  C/06  B/07  B/08  A/09  B/10
0.000 0.850 1.230 1.290 1.088 0.807 0.000 0.840 1.181 0.805
       0.2   0.1   0.1   0.5   0.4         -0.3  -0.6  -0.4
```

Figure 6: Ben440-4: Comparison of SPPS-1.6 with Mariko (k_{eff}=0.99364, Err=13pcm)

```
                                I/28
Power distribut. SPPS          1.235
Relative error in %             1.2
                             C/26  I/27
RMS Error: 3.17%           1.640 1.771
                             0.7   0.9
                          A/23  F/24  F/25
                         0.663 1.977 1.904
                          -1.2   0.9   0.7
                       C/19  A/20  C/21  F/22
                      0.565 0.673 1.894 1.888
                       -2.6  -1.5   0.4   0.7
                    A/14  C/15  A/16  F/17  I/18
                   0.206 0.545 0.670 1.954 1.723
                    -4.6  -2.4  -1.5   0.8   0.9
                 C/08  A/09  C/10  A/11  C/12  I/13
                0.194 0.205 0.563 0.658 1.615 1.200
                -6.1  -4.6  -2.6  -1.2   0.7   1.3
 C/01  A/02  C/03  A/04  C/05  A/06  F/07
0.103 0.093 0.216 0.250 0.647 0.721 1.476
 -7.8  -7.2  -5.5  -4.2  -2.0  -1.0   1.1
```

Figure 7: Ben1000-1: Comparison of SPPS-1.6 with Mariko (k_{eff}=1.01507, Err=243pcm)

```
                                                  1B/46 1A/47
Power distr. HEX2DA                               0.912 0.704
Relative error in %                                 0.1  -1.4
                                          1B/38 1B/39 1A/40 1A/41
RMS Error: 0.58%                          1.079 1.054 1.072 0.590
                                           -0.1  -0.1  -0.1  -1.7
                                  1B/30 1C/31 1C/32 1C/33 1A/34
                                  1.100 0.869 0.876 0.841 0.955
                                    0.1   0.2   0.1   0.3  -0.5
                         1B/21 1C/22 1C/23 1B/24 1B/25 1A/26 1A/27
                         1.191 0.920 0.901 1.131 1.135 1.261 0.812
                           0.3   0.4   0.3   0.0  -0.1  -0.1  -0.8
                 1B/11 1C/12 1B/13 1B/14 1B/15 1C/16 1C/17 1A/18 1A/19
                 1.211 0.973 1.198 1.175 1.173 0.945 0.932 1.179 0.622
                   0.4   0.6   0.3   0.2   0.1   0.2   0.3  -0.1  -1.5
1B/01 1C/02 1B/03 1B/04 1C/05 1C/06 1B/07 1B/08 1A/09 1B/10
1.171 0.953 1.217 1.221 0.961 0.951 1.194 1.198 1.366 0.781
  0.3   0.7   0.4   0.3   0.5   0.4   0.1  -0.1   0.0  -0.4
```

Figure 8: Ben440-1: Comparison of HEX2DA with Mariko (k_{eff}=0.99970, Err=106pcm)

```
                                                  1B/46 1A/47
Power distr. HEX2DB                               0.914 0.707
Relative error in %                                 0.2  -1.1
                                        1B/38 1B/39 1A/40 1A/41
RMS Error: 0.42%                        1.079 1.055 1.074 0.592
                                          0.0   0.0   0.1  -1.3
                              1B/30 1C/31 1C/32 1C/33 1A/34
                              1.099 0.869 0.876 0.841 0.957
                                0.0   0.1   0.1   0.3  -0.3
                    1B/21 1C/22 1C/23 1B/24 1B/25 1A/26 1A/27
                    1.188 0.918 0.900 1.131 1.135 1.262 0.815
                      0.1   0.2   0.2   0.0   0.0   0.1  -0.5
          1B/11 1C/12 1B/13 1B/14 1B/15 1C/16 1C/17 1A/18 1A/19
          1.208 0.971 1.196 1.174 1.172 0.944 0.932 1.180 0.625
            0.1   0.3   0.1   0.0   0.0   0.2   0.4   0.1  -1.1
1B/01 1C/02 1B/03 1B/04 1C/05 1C/06 1B/07 1B/08 1A/09 1B/10
1.168 0.950 1.214 1.218 0.959 0.950 1.193 1.198 1.367 0.783
  0.1   0.4   0.2   0.1   0.3   0.3   0.0   0.0   0.1  -0.2
```

Figure 9: Ben440-1: Comparison of HEX2DB with Mariko (k_{eff}=1.00064, Err=200pcm)

```
                                                  1B/46 1A/47
Power distr. HEX2DA                               0.720 0.523
Relative error in %                                -0.2  -1.3
                                        1B/38 1B/39 1A/40 1A/41
RMS Error: 0.43%                        1.032 0.907 0.820 0.454
                                          0.0  -0.1  -0.1  -1.2
                              1B/30 1C/31 1C/32 1C/33 1A/34
                              1.241 0.968 0.880 0.755 0.742
                                0.3   0.0  -0.1  -0.3  -0.3
                    1B/21 1C/22 1C/23 1B/24 1B/25 1A/26 1A/27
                    1.452 1.151 1.061 1.145 1.030 0.996 0.636
                      0.4   0.2   0.1   0.1  -0.1  -0.1  -0.4
          1B/11 1C/12 1B/13 1B/14 1B/15 1C/16 1C/17 1A/18 1A/19
          1.558 1.294 1.445 1.348 1.246 0.968 0.850 0.896 0.484
            0.5   0.3   0.3   0.3   0.1  -0.1  -0.3  -0.2  -1.0
1B/01 1C/02 1B/03 1B/04 1C/05 1C/06 1B/07 1B/08 1A/09 1B/10
1.559 1.330 1.551 1.503 1.205 1.120 1.211 1.092 1.080 0.611
  0.4   0.4   0.4   0.4   0.2   0.1   0.1  -0.1  -0.1  -0.6
```

Figure 10: Ben440-2: Comparison of HEX2DA with Mariko (k_{eff}=1.02444, Err=59pcm)

```
                                                    1B/46 1A/47
Power distr. HEX2DA                                 0.826 0.592
Relative error in %                                   0.0  -2.1
                                              1B/38 1B/39 1A/40 1A/41
RMS Error: 1.02%                              1.019 0.959 0.901 0.507
                                                0.3   0.1  -0.7  -2.5
                                    1B/30 1C/31 1C/32 1C/33 1A/34
                                    1.124 0.980 0.939 0.881 0.820
                                      0.5   0.7   0.5   0.2  -1.4
                          1B/21 1C/22 1C/23 1B/24 1B/25 1A/26 1A/27
                          1.265 1.101 1.048 1.100 1.055 1.080 0.707
                            0.5   0.8   0.7   0.3   0.1  -0.8  -1.9
                 1B/11 1C/12 1B/13 1B/14 1B/15 1C/16 1C/17 1A/18 1A/19
                 1.321 1.198 1.272 1.212 1.170 1.025 0.988 1.009 0.529
                   0.6   0.8   0.5   0.4   0.3   0.5   0.1  -1.0  -2.5
1B/01 1C/02 1B/03 1B/04 1C/05 1C/06 1B/07 1B/08 1A/09 1B/10
1.295 1.203 1.327 1.306 1.149 1.103 1.162 1.115 1.161 0.721
  0.6   0.9   0.6   0.5   0.7   0.7   0.2   0.0  -0.9  -1.0
```

Figure 11: Ben440-3: Comparison of HEX2DA with Mariko (k_{eff}=1.01362, Err=104pcm)

```
                                                    1B/46 1A/47
Power distr. HEX2DB                                 0.827 0.594
Relative error in %                                   0.1  -1.8
                                              1B/38 1B/39 1A/40 1A/41
RMS Error: 0.89%                              1.019 0.960 0.902 0.508
                                                0.3   0.2  -0.6  -2.2
                                    1B/30 1C/31 1C/32 1C/33 1A/34
                                    1.123 0.980 0.939 0.882 0.822
                                      0.4   0.6   0.5   0.3  -1.2
                          1B/21 1C/22 1C/23 1B/24 1B/25 1A/26 1A/27
                          1.263 1.100 1.048 1.100 1.056 1.081 0.709
                            0.4   0.7   0.6   0.2   0.1  -0.8  -1.6
                 1B/11 1C/12 1B/13 1B/14 1B/15 1C/16 1C/17 1A/18 1A/19
                 1.319 1.197 1.270 1.211 1.169 1.025 0.988 1.009 0.531
                   0.4   0.7   0.4   0.3   0.3   0.5   0.2  -1.0  -2.1
1B/01 1C/02 1B/03 1B/04 1C/05 1C/06 1B/07 1B/08 1A/09 1B/10
1.293 1.201 1.325 1.304 1.148 1.102 1.161 1.115 1.161 0.723
  0.5   0.8   0.4   0.4   0.6   0.6   0.2   0.0  -0.9  -0.8
```

Figure 12: Ben440-3: Comparison of HEX2DB with Mariko (k_{eff}=1.01456, Err=198pcm)

```
                          1F/28
Power distr. HEX2DA       1.211
Relative error in %        -0.8
                       1C/26 1F/27
RMS Error: 1.43%       1.630 1.739
                         0.0  -0.9
                    1A/23 1E/24 1E/25
                    0.680 1.958 1.875
                      1.3  -0.1  -0.8
                 1C/19 1A/20 1C/21 1E/22
                 0.587 0.692 1.884 1.860
                   1.1   1.2  -0.2  -0.9
              1A/14 1C/15 1A/16 1E/17 1F/18
              0.220 0.565 0.689 1.935 1.690
                2.2   1.1   1.2  -0.1  -1.0
         1C/08 1A/09 1C/10 1A/11 1C/12 1F/13
         0.211 0.220 0.585 0.674 1.603 1.174
           1.9   2.3   1.1   1.3  -0.1  -0.9
1C/01 1A/02 1C/03 1A/04 1C/05 1A/06 1E/07
0.115 0.103 0.233 0.267 0.669 0.738 1.455
  3.0   2.9   2.0   2.1   1.2   1.3  -0.3
```

Figure 13: Ben1000-1: Comparison of HEX2DA with Mariko (k_{eff}=1.01427, Err=167pcm)

```
                          1F/28
Power distr. HEX2DB       1.212
Relative error in %        -0.7
                       1C/26 1F/27
RMS Error: 0.53%       1.634 1.746
                         0.3  -0.6
                    1A/23 1E/24 1E/25
                    0.678 1.967 1.883
                      0.9   0.4  -0.4
                 1C/19 1A/20 1C/21 1E/22
                 0.581 0.689 1.891 1.868
                   0.0   0.8   0.3  -0.5
              1A/14 1C/15 1A/16 1E/17 1F/18
              0.216 0.558 0.686 1.943 1.696
                0.3   0.0   0.8   0.3  -0.6
         1C/08 1A/09 1C/10 1A/11 1C/12 1F/13
         0.206 0.216 0.579 0.672 1.608 1.176
          -0.7   0.3   0.0   0.8   0.2  -0.8
1C/01 1A/02 1C/03 1A/04 1C/05 1A/06 1E/07
0.111 0.100 0.227 0.262 0.662 0.736 1.457
 -0.6  -0.2  -0.5   0.4   0.2   1.0  -0.2
```

Figure 14: Ben1000-1: Comparison of HEX2DB with Mariko (k_{eff}=1.01475, Err=214pcm)

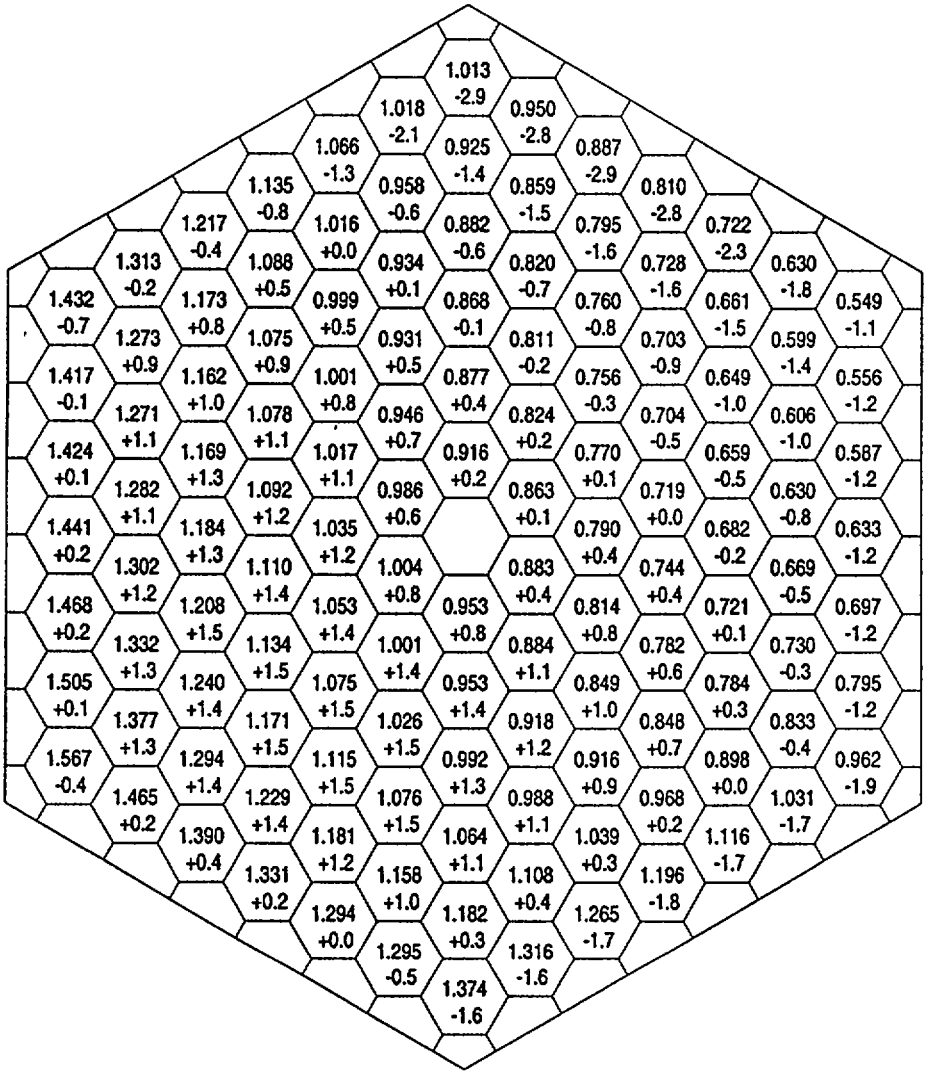

Figure 15: Ben440-2: Relative pin-wise power distribution by HEX2DB and absolute errors in % for assembly 41