Deterministic Two-Dimensional MOX Fuel Assembly Transport Calculations Without Spatial Homogenization

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ABSTRACT

As part of the effort for testing the ability of current transport codes to treat reactor core problems without spatial homogenization, the lattice code HELIOS was employed to perform criticality calculations. A basis for testing was seven-group form of the C5 MOX fuel assembly problem specified by Cavarec *et. al.* [1]. The problem, known as C5G7 MOX Benchmark is described in the Benchmark Specification [2] and comprises two cases – two and three-dimensional geometry. There are four fuel assemblies – two of them are MOX fuel assemblies and the other two are uranium dioxide assemblies. Each fuel assembly is made up of a 17x17 lattice of square fuel-pin cells. Fuel pin compositions are specified in the Benchmark Specification, which also provides seven-group transport corrected isotropic scattering cross-sections for UO_2, the three MOX enrichments, the guide tubes, the fission chamber and the moderator. This paper presents the methodology employed in solving the C5 MOX Fuel Assembly Problem using the transport code HELIOS. It presents results of eigenvalues calculation and also the pin powers using the Benchmark cross sections library and the specified geometry.

1. INTRODUCTION

HELIOS [3] is a two-dimensional (2-D) current-coupling collision-probability code. The version of HELIOS used in this project is a special version developed by Studsvik Scandpower to analyze this problem – it skips the resonance and depletion calculations. HELIOS typically is used for lattice burnup calculations using 45 or 112 energy group nuclear data library based on ENDF-B/VI. In this particular study HELIOS uses a special cross section library where the isotopes and their cross sections are the materials cross sections provided in the Benchmark specification. The auxiliary program BABEL was used to set up this special library in the format required by HELIOS. This library consists of seven group cross sections and seven "isotopes" that represent four fuel+clad mixtures, fission chamber, guide tube and moderator.

The HELIOS package consists of four codes. AURORA is an input pre-processing code, which is used for treatment of the system geometry and assignment of the compositions to the different regions. This code also prepares the input to be used by the calculation module HELIOS. The output of HELIOS then is processed by the ZENITH code. All these codes share one data base which is accessed and maintained by the subroutine package HERMES. Another code included in the HELIOS package is ORION, which is used to verify the geometry, and the material and temperature overlays used. It draws the lattice shape as a post script file. Two input files are necessary to perform calculations with HELIOS. One is the AURORA input, the other is for ZENITH to process the output.

The objective of this paper is to analyze the C5G7 MOX benchmark problem with the HELIOS code. Several cases with different geometry and current coupling order were studied. The results from these sensitivity studies are analyzed and discussed. The obtained results are presented in the format required from the specification.

2. THEORY

HELIOS solves the integral neutron transport equation using the current coupling collision probability (CCCP) method. The system is divided into **E** space elements which are further divided into flat–flux regions **i**. All the space elements are coupled by interface currents and all these elements are internally treated by collision probabilities (CP). The periphery of each space element is spatially discretized into faces **s**. The half sphere of incoming directions of each of this faces has an angular discretization into sectors **k**.

Let $\mathbf{X_i}$ and $\mathbf{Y_{sk}}$ be the vectors of response fluxes in all the regions of a space element due to a unit source in region **i** and a unit in-current through sector **k** of face **s**. The fluxes $\mathbf{\Phi}$ in all the regions of the system are obtained as linear combination of the sources **Q** in all the regions and the in-currents $\mathbf{j^-}$ through all the sectors on all the faces of the system [4],

$$\Phi = \mathrm{X}Q + Yj^{-}$$

where, **X** and **Y** are diagonal block matrices of ExE blocks. Each block is the local matrix of a space element and has as columns the vectors $\mathbf{X_i}$ and $\mathbf{Y_{sk}}$. These response fluxes are obtained by CP locally in the space elements.

The coupling of the space elements is done by the current coupling (CC) method using interface currents $\mathbf{j^-}$. Let P_i be the vector of escape probabilities through all the sectors of a space element due to a unit source in region **i**. Further, let $\mathbf{R_{sk}}$ be the vector of transmission probabilities to all its sectors due to a unit in-current through sector **k** of face **s**. The out-currents j^+ through all the sectors of the system can then be written as a linear combination of $\mathbf{j^-}$ and **Q** [4],

$$j^{+} = Rj^{-} + PQ$$

where, **R** and **P** are diagonal block matrices of ExE blocks. Each block is the local matrix of a space element and has as columns the vectors, which are also obtained by CPs.

One more relation between $\mathbf{j^+}$ and $\mathbf{j^-}$ is needed. Each current that exits space element through a sector enters at the same time another space element, then

$$j^{+} = Hj^{-}$$

where, **H** is a square matrix and has as many as the number of sectors in the system, where each row has one non-zero entry.

3. METHODOLOGY

Since the problem appeared to be too large for our computational capabilities, it was decided to examine only the diagonal half of it (1/8-th of the core). There are four fuel assemblies – two MOX and two UO_2. The fuel assembly configuration is shown in Figure 1. Each fuel assembly is made up of a 17x17 lattice of square fuel-pin cells. Fuel pin compositions are presented in Figure 2. The same boundary conditions given in the benchmark specifications were used.

HELIOS allows the user to model fuel assemblies in different ways. Varying degrees of complexity can be used to define the fuel assembly. Usually, the components in a HELIOS assembly will be the pin cell consisting of fuel, gap, clad and surrounding moderator. The fuel, clad and moderator can be subdivided in numerous ways into meshes (called "regions" in HELIOS jargon). In the problem described in this paper two regions were used – fuel-clad mixture and moderator - as given in the benchmark specifications. The fuel-clad region is divided into three annular meshes.

Three cases with different geometry of the moderator region were studied. A coarse mesh was considered for the first case, as shown in Figure 3. In this case the moderator region is divided into four meshes. For the second case (fine mesh) the moderator region was divided into eight meshes (Figure 4). In the last case the moderator was again divided into eight meshes but in different way – “sun mesh” (Figure 5). An ORION picture of the entire system can be seen in Figure 6. For all the three cases HELIOS used two different coupling orders – “2” and “4”. The best results could be obtained using coupling order “0” (CPs without current coupling), however, because of memory limitations only coupling orders “2” and “4” were examined in detail and their results are presented in this paper. Other coupling orders also were used and calculations with them were performed for sensitivity studies.

4. RESULTS

The results obtained with HELIOS for the 2-D benchmark configuration are presented and discussed. These results are the eigenvalues and peak to average pin power ratios for all of the cases given in Table 1 and Table 2 for coupling orders 2 and 4 respectively. Pin power distributions for UO_2 and MOX assemblies for case 2 are given in Tables 3 to 5 and for case 3 are given in Tables 6 to 8.

More calculations were done using the geometry modeling flexibility of the code. The fuel-clad pin was varied from one to five annular meshes and for every case calculations were performed. These results are not given in this work because it turned out that the impact of changes in the fuel-clad region modeling is insignificant for the final results.

The changes in the moderator mesh from Figure 3 to Figure 4 and finally to Figure 5 affect the eigenvalues and the peak to average pin power ratio. From the results in Table 1 and Table 2 it can be seen that both the eigenvalue and the peak to average pin power ratio increase slightly with the number of moderator meshes. The same behavior is observed when going from case 2 (fine mesh) to case 3 (sun mesh).

Sensitivity studies were done using not only coupling orders “2” and “4” but also “1”, “3”, “5”, “6” and “7”. The results for the last five cases were far away from the reference eigenvalue in the specification (given for the geometry checking out). We decided that these results have no practical interest and therefore are not presented in this work. From these calculations it was determined that the results are more dependent to the change in the coupling order than the change in the refinement of the meshes.

CONCLUSIONS

The benchmark analyzed in this paper is an interesting transport problem because of the complex flux behavior due to the small size of the core and the heterogeneity at the MOX/UO_2 interface. Such a problem with steep flux gradients is hard to be analyzed accurately with the widely applied diffusion theory codes because of the diffusion approximation. Using HELIOS for these calculations we tried to contribute to the efforts for testing the ability of current transport codes to treat reactor core problems without spatial homogenization.

The impact of using different code modeling options on the obtained results is discussed and analyzed. Numerical results are presented for the different modeling used.

The future work involves detail comparative analysis of these results, and the results obtained with HELIOS, using 7 group pin-homogenized cross-sections. In addition, pin-by-pin nodal diffusion calculations will be performed using the pin homogenized cross-sections. These comparisons will contribute to understand and evaluate the errors introduced with pin homogenization and diffusion approximation in reactor core pin-by-pin calculations.

REFERENCES

1. Cavarec, C., et al., “The OECD/NEA Benchmark Calculations of Power Distributions within Assemblies,” Electricité de France, Sept. 1994.
2. Lewis, E., et al., “Benchmark Specification for Deterministic 2-D/3-D MOX Fuel Assembly transport calculations without spatial homogenization (C5G7 MOX),” NEA/NSC, 2001.
3. “HELIOS Methods”, StudsvikScandpower, 2000.
4. Juan J Casal, Rudi JJ Stamm’ler, Eduardo A Villarino and Aldo A Ferri, “HELIOS: Geometric Capabilities of a new Fuel-Assembly Program,” Proc. Int. Topl. Mtg. Advances in Mathematics, Computations, and Reactor Physics, Pittsburgh, Pennsylvania, April 28 – May 2, 1991, Vol. 2, p. 10.21-1.

Figure 1. Core layout

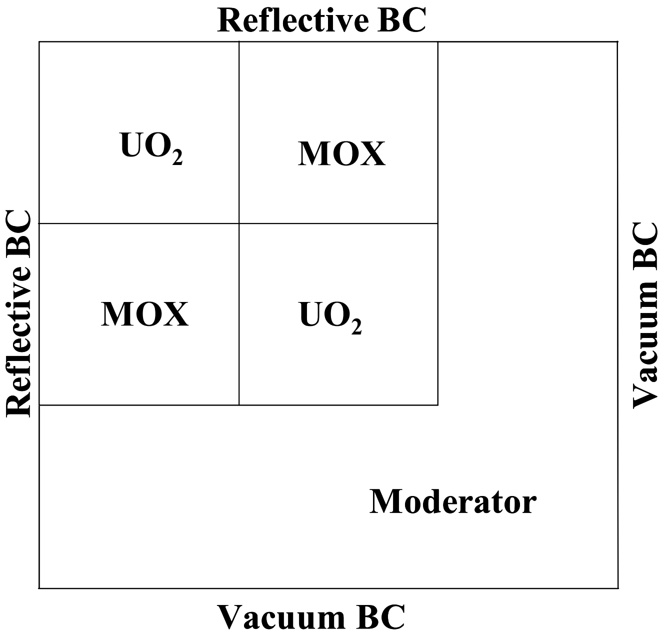

Figure 2. Fuel pin compositions

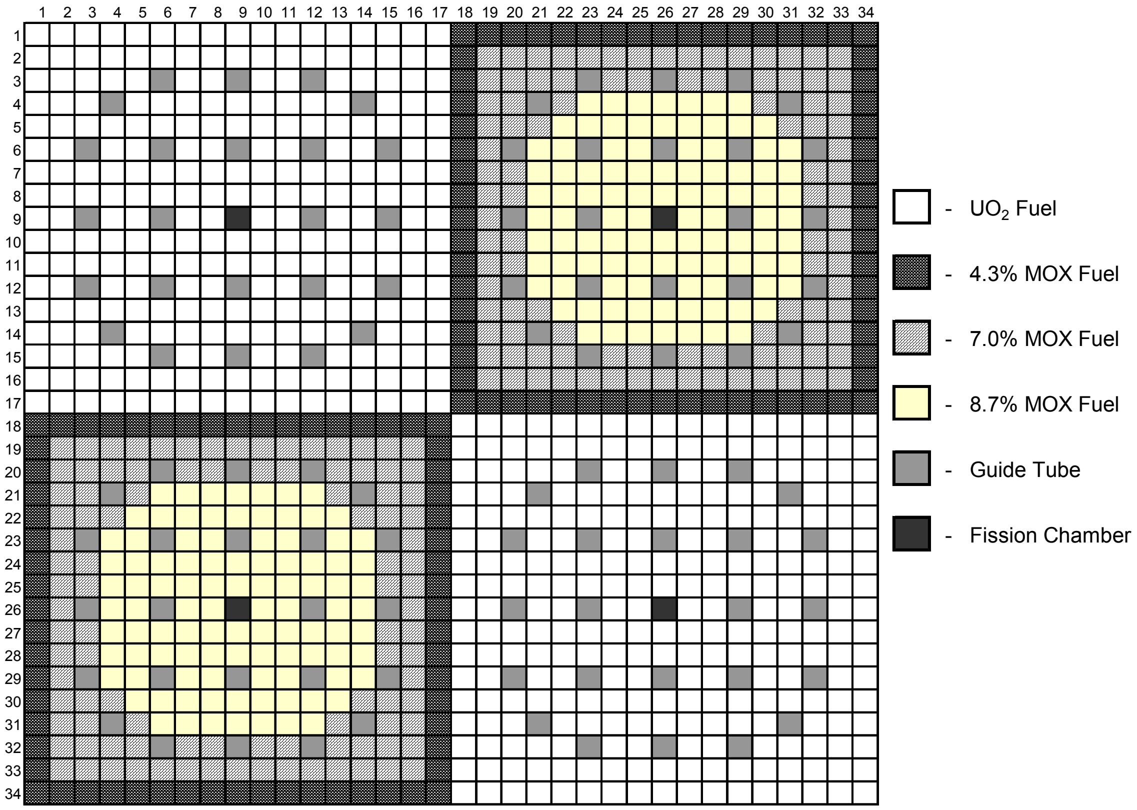

Figure 3. Case 1 geometry of the fuel pin layout– coarse mesh

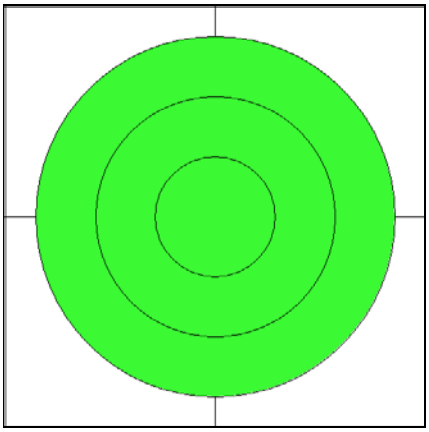

Figure 4. Case 2 geometry of the fuel pin layout– fine mesh

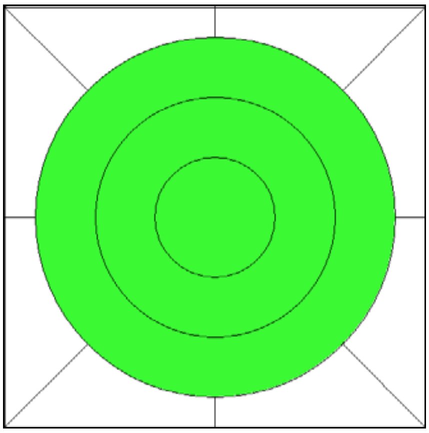

Figure 5. Case 3 geometry of the fuel pin layout– sun mesh

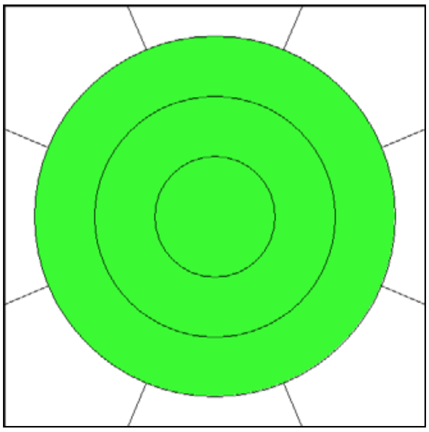

Figure 6. Orion code output

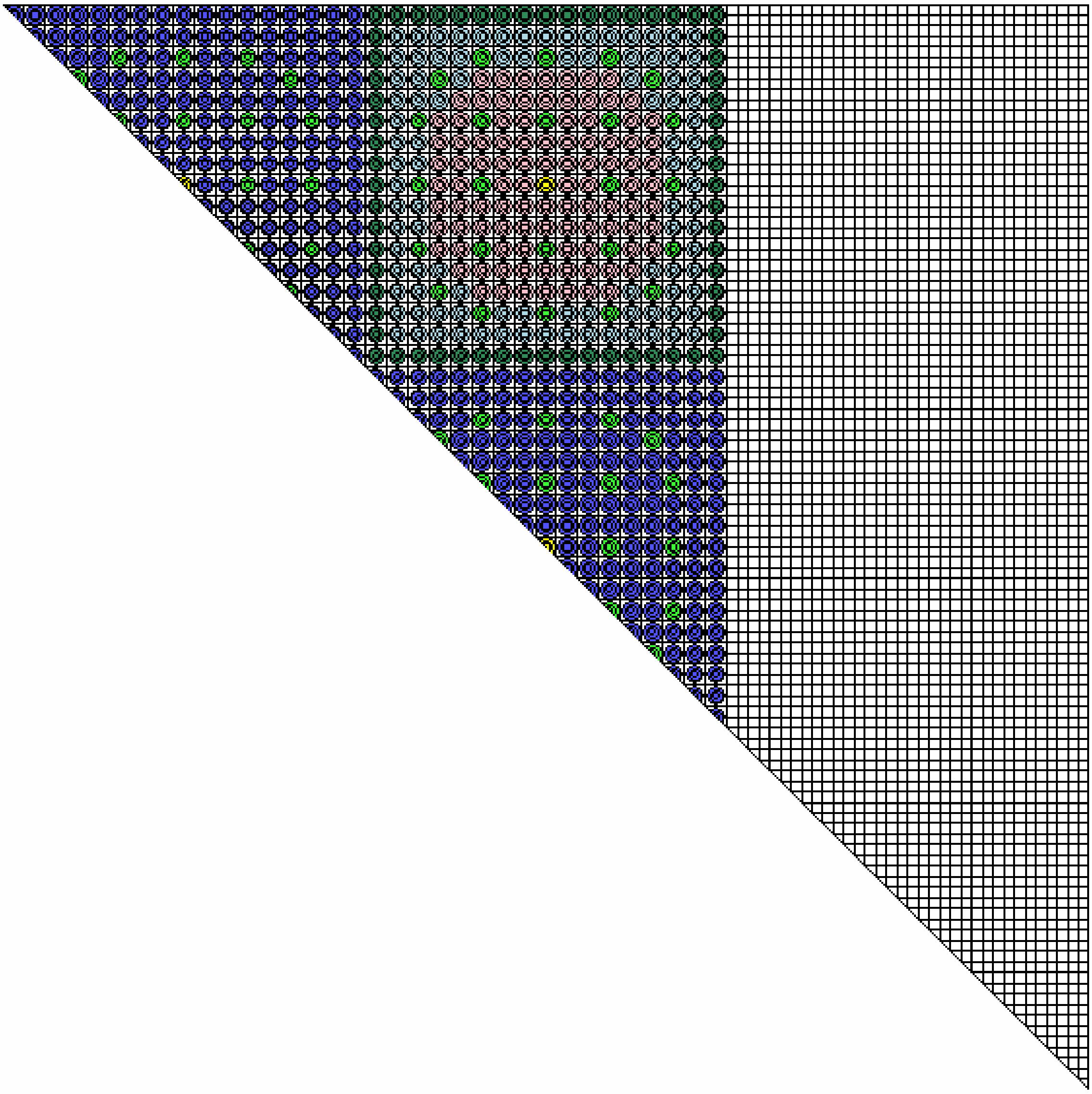

Table 1. Results for coupling order "2"

	Eigenvalue	Peak to average pin power ratio
Case 1 (coarse mesh)	1.1975467	2.584
Case 2 (fine mesh)	1.1976986	2.597
Case 3 (sun mesh)	1.1980989	2.603

Table 2. Results for coupling order "4"

	Eigenvalue	Peak to average pin power ratio
Case 1 (coarse mesh)	1.1925858	2.534
Case 2 (fine mesh)	1.1927292	2.545
Case 3 (sun mesh)	1.1932994	2.545

Table 3. UO$_2$ Pin powers for case 2 and coupling order “4”[1]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	2246	2251	2260	2272	2279	2275	2235	2197	2161	2100	2042	1984	1891	1784	1658	1504	1294
2		2262	2288	2322	2358	2411	2308	2265	2283	2166	2107	2102	1959	1825	1680	1512	1293
3			2364	2480	2515	▨	2419	2368	▨	2267	2206	▨	2091	1952	1740	1531	1297
4				▨	2545*	2490	2350	2299	2323	2199	2145	2169	2111	▨	1831	1558	1304
5					2465	2465	2335	2285	2310	2187	2132	2149	2047	2002	1855	1586	1310
6						▨	2383	2335	▨	2236	2176	▨	2052	1958	▨	1626	1311
7							2272	2230	2256	2135	2077	2083	1945	1851	1785	1556	1290
8								2190	2216	2098	2041	2043	1907	1814	1751	1530	1271
9									▨	2125	2066	▨	1932	1836	▨	1550	1256
10										2011	1958	1962	1832	1744	1686	1474	1225
11											1907	1913	1790	1707	1648	1440	1198
12												▨	1811	1732	▨	1449	1173
13													1728	1695	1581	1358	1128
14														▨	1489	1276	1077
15															1337	1189	1022
16																1092	961
17																	885

Table 4. MOX Pin powers for case 2 and coupling order “4”[1]

	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	1332	1077	945	870	818	772	717	667	622	572	525	483	437	398	378	416	619
2	1316	1365	1186	1105	1062	1046	930	859	837	739	677	654	570	505	473	527	613
3	1309	1343	1195	1177	1124	▨	948	867	▨	751	684	▨	604	538	478	518	609
4	1311	1354	1267	▨	1118	1128	971	891	874	767	705	699	588	▨	511	523	608
5	1315	1386	1298	1190	1165	1085	941	866	850	746	684	674	616	537	518	535	608
6	1315	1437	▨	1283	1146	▨	983	900	▨	782	711	▨	616	574	▨	556	608
7	1295	1360	1228	1167	1055	1037	913	843	831	728	666	650	566	526	487	527	602
8	1277	1338	1203	1143	1034	1018	899	832	820	719	658	640	557	517	479	521	597
9	1261	1373	▨	1193	1075	▨	943	867	▨	755	686	▨	586	539	▨	538	593
10	1232	1294	1167	1109	1005	991	876	812	801	703	643	627	546	507	470	511	585
11	1206	1269	1147	1094	992	977	863	800	788	693	635	620	541	504	466	506	579
12	1181	1298	▨	1167	1047	▨	906	833	▨	728	664	▨	578	539	▨	524	574
13	1139	1212	1144	1051	1035	972	847	783	773	680	626	620	567	495	479	496	564
14	1094	1145	1085	▨	971	986	854	789	778	687	634	631	533	▨	466	478	555
15	1051	1103	1002	1002	967	▨	828	764	▨	670	614	▨	547	489	436	471	551
16	1021	1111	1003	957	934	930	836	781	765	682	629	610	535	477	447	493	560
17	1025	923	868	831	799	767	722	679	639	593	550	509	464	425	404	433	600

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[1] All the pin powers are multiplied by 10^3

Table 5. UO_2 Pin powers for case 2 and coupling order "4"[1]

	18	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**
18	802	797	778	757	732	705	666	628	592	550	510	473	432	397	377	398	520
19		835	841	835	822	814	750	707	684	621	576	550	492	446	420	434	546
20			876	906	896	▨	808	759	▨	670	621	▨	541	492	447	449	553
21				▨	903	858	783	736	716	649	605	585	546	▨	470	455	549
22					857	833	764	720	700	636	593	572	523	499	470	454	539
23						▨	761	718	▨	637	592	▨	514	478	▨	454	524
24							704	666	650	591	550	528	474	440	431	424	502
25								632	616	561	523	501	450	417	409	403	479
26									▨	549	510	▨	440	407	▨	393	455
27										500	466	448	401	372	365	360	427
28											434	417	375	348	341	336	399
29												▨	364	338	▨	322	371
30													333	317	300	289	341
31														▨	274	262	312
32															247	243	288
33																240	277
34																	298

Table 6. UO_2 Pin powers for case 3 and coupling order "4"[1]

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
1	2246	2249	2259	2270	2276	2275	2233	2194	2161	2098	2040	1984	1890	1783	1658	1504	1296
2		2260	2287	2323	2354	2414	2303	2261	2287	2163	2103	2105	1956	1826	1680	1513	1295
3			2360	2486	2516	▨	2424	2373	▨	2272	2211	▨	2092	1957	1739	1532	1299
4				▨	2545	2497	2345	2294	2328	2195	2141	2175	2111	▨	1836	1560	1307
5					2455	2470	2330	2281	2315	2182	2127	2154	2041	2002	1857	1584	1312
6						▨	2388	2339	▨	2241	2181	▨	2056	1964	▨	1631	1315
7							2265	2225	2261	2130	2073	2087	1941	1848	1790	1554	1292
8								2184	2220	2093	2036	2048	1903	1811	1756	1529	1273
9									▨	2130	2070	▨	1937	1841	▨	1555	1260
10										2006	1954	1967	1828	1741	1691	1473	1227
11											1903	1918	1787	1704	1653	1440	1200
12												▨	1815	1737	▨	1453	1176
13													1722	1696	1583	1357	1130
14														▨	1494	1278	1079
15															1336	1191	1024
16																1092	963
17																	886

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[1] All the pin powers are multiplied by 10^3

Table 7. MOX Pin powers for case 3 and coupling order “4”[1]

	18	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**
1	1333	1078	947	872	820	774	719	668	623	572	526	484	438	397	377	415	616
2	1317	1366	1188	1107	1061	1051	929	859	840	738	676	656	568	504	471	524	609
3	1310	1344	1195	1183	1127	▨	954	872	▨	756	688	▨	605	539	476	515	605
4	1312	1355	1274	▨	1121	1135	969	890	879	766	703	702	588	▨	512	520	604
5	1316	1384	1301	1192	1161	1091	940	865	855	744	683	677	613	536	517	531	604
6	1316	1442	▨	1290	1151	▨	989	905	▨	786	714	▨	619	575	▨	555	604
7	1295	1357	1234	1165	1053	1043	911	842	835	726	665	653	564	524	487	523	598
8	1277	1336	1209	1141	1033	1024	898	831	824	718	657	643	555	515	479	517	593
9	1262	1377	▨	1200	1081	▨	948	872	▨	760	689	▨	588	540	▨	537	589
10	1232	1292	1173	1107	1004	997	875	810	806	701	642	630	544	504	470	506	581
11	1206	1267	1153	1092	991	982	862	798	793	691	634	623	539	501	467	502	575
12	1182	1302	▨	1173	1052	▨	911	837	▨	731	666	▨	580	540	▨	522	570
13	1140	1209	1147	1052	1032	977	846	782	777	678	624	622	564	494	478	492	560
14	1095	1146	1090	▨	973	991	852	788	782	685	632	633	532	▨	466	475	551
15	1052	1103	1001	1007	968	▨	832	767	▨	673	616	▨	547	490	433	468	546
16	1022	1112	1003	958	932	933	834	779	767	680	627	610	533	475	445	489	555
17	1027	924	868	831	799	767	722	679	639	593	549	509	463	424	402	429	595

Table 8. UO_2 Pin powers for case 3 and coupling order “4”[1]

	18	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**
18	802	798	780	758	734	707	667	628	593	550	510	473	432	396	376	396	516
19		835	841	836	822	816	749	706	685	620	575	550	490	445	418	431	542
20			875	909	897	▨	810	761	▨	671	621	▨	540	492	445	446	548
21				▨	903	860	781	735	717	647	602	585	545	▨	469	452	544
22					853	834	762	718	701	634	590	571	520	497	467	450	534
23						▨	762	719	▨	637	591	▨	514	477	▨	451	520
24							701	664	650	588	547	528	472	437	429	419	497
25								629	616	559	520	500	447	414	407	399	474
26									▨	549	510	▨	439	406	▨	390	450
27										497	463	447	399	369	364	356	422
28											431	416	373	345	339	332	394
29												▨	362	336	▨	319	367
30													329	315	298	286	337
31														▨	272	260	308
32															244	240	284
33																236	273
34																	293

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[1] All the pin powers are multiplied by 10^3