"HELIOS: Analysis of MOX Critical Experiments"

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ABSTRACT

Thirty UO_2–PuO_2 fueled light-water moderated lattice critical experiments have been analyzed with HELIOS at the Nuclear Engineering Program of the Pennsylvania State University, in collaboration with Studsvik-Scandpower. These experiments were performed at Battelle Pacific Northwest Laboratories in the early 80s. HELIOS is an advanced lattice physics code based on two-dimensional high order transport theory with complete geometric flexibility. The thirty cases have been analyzed already with HELIOS as single pin cell cases and these results are used for comparison. The present study involves the development of the HELIOS input decks for complete two-dimensional representations of the estimated critical cores. The sensitivity of the calculated values of k_{eff} for various options such as reflector thickness, energy groups, coupling order and the modeling approach used in this analysis are discussed for selected cases. Finally, the results of HELIOS have been verified by comparison with the experimental results.

INTRODUCTION

The experimental determination of the critical sizes of fully - reflected lattices of UO_2–PuO_2 fueled, light-water moderated systems were provided in the Critical Approach Facility under the Plutonium Utilization Program. The major emphasis of this program was to determine the number of rods required for the core to be just critical (k_{eff} of unity) with the rods arrayed uniformly and other parameters such as reflector savings, λ, and geometrical buckling, B_g^2. (Liikala R.C., 1972 and Uotinen V.O., 1972)

The objective of this paper is to apply the advanced lattice physics code HELIOS, which is based on two-dimensional high order transport theory with complete geometric flexibility, to analyze these experiments. The 30 cases are divided into five different sets of UO_2–PuO_2. The first three sets utilized natural UO_2 fuel mixed with 2 wt% PuO_2 with three different ^{240}Pu concentrations (8, 16 and 24 at%). The fourth set used natural UO_2 fuel mixed with 4 wt% Pu. The final set utilized depleted (0.16 at% ^{235}U) UO_2 fuel mixed with 1.5 wt% PuO_2 that had been designed for the Experimental Boiling-Water Reactor (EBWR) plutonium demonstration experiment. The lattices cover a broad range of water-to-rod volume ratios.

METHODOLOGY

HELIOS is the code used in this project to calculate k_{eff}. (HELIOS, 2000) There are two options of cross-section libraries, 89 and 34 groups in version 1.4, and also 45 and 112 groups in version 1.6, based on ENDF/B-VI files. The transport calculations are done in the energy-group structure of the library, using per energy group the so-called CCCP method (Current Coupling Collision Probabilities). In this method, the geometric system of core-plus-reflector is divided into hexagonal space elements whose side-to-side distance is equal to the lattice pitch of the fuel rods in the core. The space elements are coupled with each other—and also with the boundaries—by interface currents, while the properties of each space element are obtained from collision probabilities. Because the pins in the pin-cell space elements are treated explicitly by the collision-probabilities, the CCCP method is done in the true, heterogeneous geometry, avoiding any spatial homogenization.

Input decks for the individual experiments have been developed using the data in Table 1. For the small and medium core assemblies (less than 500 rods per assembly), they were modeled in full core geometry. The large core assemblies (more than 500 rods per assembly) were modeled in one-sixth symmetric geometry because of the limitation of memory.

Table 1: Lattice data (from experiments)

UO_2 –2 wt.% PuO_2 rods in H_2O

Case	Lattice pitch (in.)	H/Pu atom ratio	H_2O/rod volume ratio	No. of rods	Reflector savings (cm)
8% ^{240}Pu rods (average temperature 22°C) Height 91.44 cm.					
1	2.032	238	1.211	319.7±0.1	7.04±0.04
2	2.3622	391	1.987	192.4±0.1	7.52±0.03
3	2.667	554	2.808	152.1±0.2	7.70±0.06
4	2.9032	693	3.513	147.5±0.1	7.11±0.03
5	3.3528	991	5.019	163.1±0.1	6.69±0.06
6	3.524	1113	5.635	179.5±0.2	6.35±0.06
16% ^{240}Pu rods (average temperature 23°C) Height 91.44 cm.					
7	2.3622	391	1.987	245.6±0.1	7.85±0.03
8	2.667	554	2.808	194.3±0.1	7.91±0.06
9	2.90322	693	3.513	187.5±0.1	7.32±0.04
10	3.3528	991	5.019	221.1±0.1	6.95±0.06
11	3.524	1113	5.635	254.6±0.1	5.85±0.04
24% ^{240}Pu rods (average temperature 24°C)					
Height 91.44 cm.					

12	2.032	238	1.211	519.5±0.1	8.21±0.04
13	2.3622	391	1.987	286.1±0.1	7.62±0.04
14	2.667	554	2.808	233.2±0.1	7.50±0.05
15	2.90322	693	3.513	232.1±0.1	7.00±0.03
16	3.3528	991	5.019	293.2±0.1	5.79±0.03
17	3.52044	1113	5.635	365.3±0.1	5.42±0.04

UO_2 –4 wt.% ^{240}Pu rods in H_2O (average temperature 25°C) Height 91.44 cm.					
18	2.159	152.8	1.5	252.6±0.5	7.89±0.04
19	2.3622	203.3	1.993	178.9±0.2	7.55±0.03
20	2.667	288.7	2.815	138.9±0.4	7.54±0.04
21	2.90322	413.9	3.521	122.4±0.1	7.29±0.01
22	3.52044	578.1	5.647	123.6±0.7	6.46±0.06
23	4.064	804.8	7.859	180.9±2.1	5.30±0.17
24	4.318	922	9	271.9±0.5	5.36±0.09

UO_2 -1.5 wt.% ^{240}Pu rods in H_2O (average temperature 25°C) Height 123.19 cm.					
25	1.397	230	0.8382	1487±3	8.40±0.06
26	1.524	326	1.187	829±7	7.99±0.10
27	1.8034	567	20.63	484±1	7.27±0.03
28	2.032	794	2.889	420±1	6.93±0.03
29	2.286	1077	3.922	452±2	6.75±0.03
30	2.3622	1169	4.255	488±2	6.64±0.05

The radial reflector is modeled explicitly by adding rings of reflector (water) cells. It requires at least 15 cm of reflected material in order to reflect or scatter leakage neutrons back to the core. Fig. 1 shows the geometry created by the HELIOS input viewer Orion. The angular discretization of the coupling currents at the interface segments of the space elements was chosen to be $k = 2$. Since HELIOS models only two-dimensional geometry, one has to calculate the axial bucklings, B_z^2, to account for neutron leakage in the axial direction. It is determined by:

$$B_z^2 = \left[\frac{p}{H + 2l}\right]^2$$

Where: H = active fuel height
λ = reflector savings

Many of the lattices used in the experiments have a large H_2O-fuel volume ratio. Therefore, there must be extra coolant-mesh rings around the fuel pins to be able to describe the flux gradients towards the pins. It should be done systematically, starting with 0.08 cm and gradually becoming thicker, but not more than 0.20 cm, e.g. 0.08, 0.10, 0.12, 0.14, 0.16, 0.18.

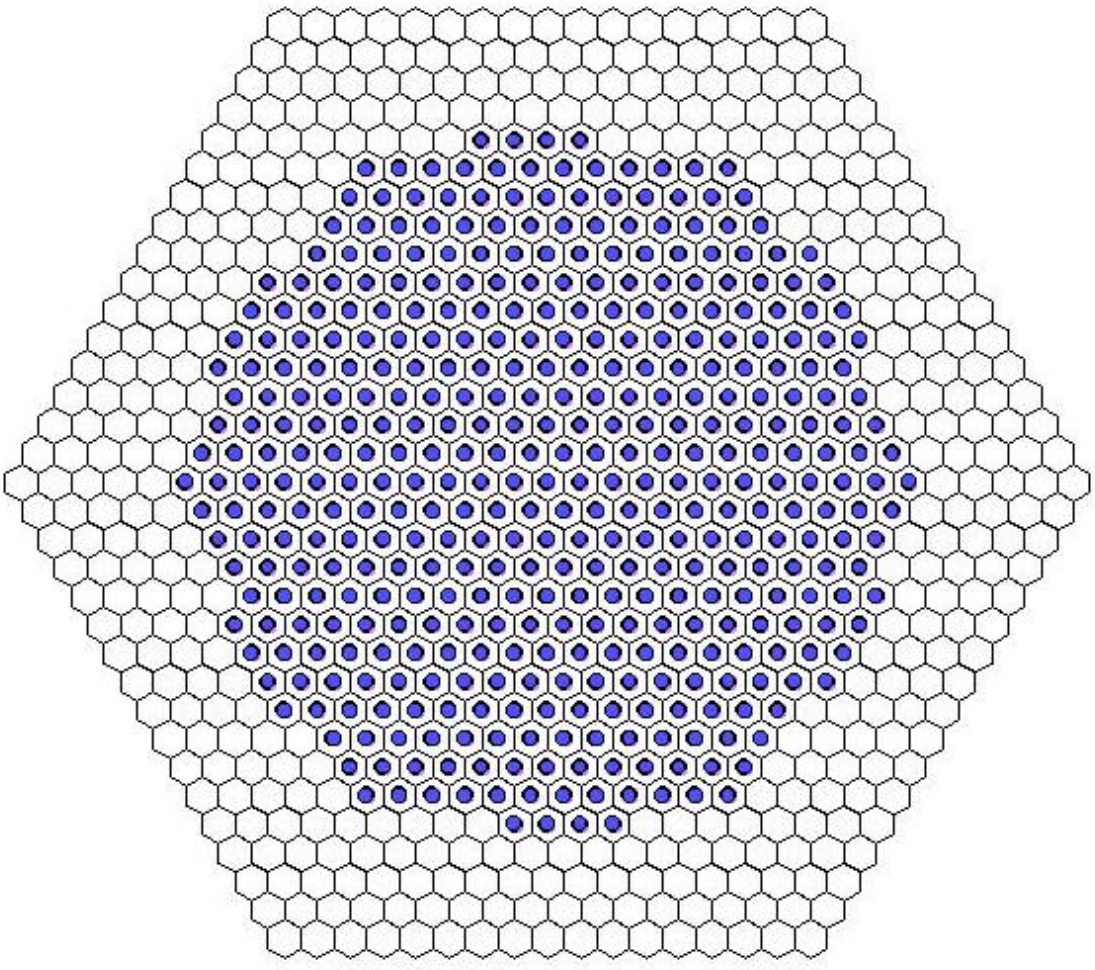

Fig. 1 Example of the geometry

SENSITIVITY STUDIES

In this section, the sensitivity studies done to approach the model criteria are described. In Table 2, the results obtained from parametric studies for five cases (4, 9, 15, 22 and 28) are summarized. Each case was selected to be representative of the individual group. The sensitivity of HELIOS predictions for k_{eff} to different modeling assumptions is the number of energy groups in the cross section library, 34 vs. 89 groups (for HELIOS version 1.4), and 45 groups (for version 1.6), and current coupling modeling (k1 to k2).

Table 2 Results from sensitivity studies

Case No.	HELIOS-1.4				HELIOS-1.6	
	34-groups		89-groups		45-groups	
	k1	k2	k1	k2	k1	k2
4	1.04987	1.00030	1.04744	0.99605	1.04864	0.99804
9	1.01082	0.99615	1.03778	0.99235	1.03937	0.99385
15	1.04112	1.00189	1.01875	0.99771	1.03976	0.99990
22	1.04140	1.00342	1.03793	0.99922	1.04029	1.00173
28	1.06721	1.00973	1.06561	N/A	1.06432	1.00790

These sensitivity studies indicate that the best agreement with measured values is obtained when the k2 option for current coupling is used with 34 and 45 energy groups library cross-section. The notation N/A means that these studies could not be performed owing to memory limitations. The sensitivity to the current coupling option is much stronger than that to the number of energy groups in the cross-section library. This confirms that isotropic (cosine) currents are not suitable in lattice calculations. In addition, the sensitivity of the results to the shape of modeled cores was studied. Since these cores are estimated ones, any assumption about the shape introduces an uncertainty. The best agreement was obtained using the shape shown in Fig. 1.

RESULTS AND DISCUSSION

The experimental and calculated results are shown in Table 3. The obtained results (k_{eff} values) with 2D HELIOS calculations for both versions are compared with the single pin-cell HELIOS calculation predictions and the estimated values taken from Ref. 2. The experimental value for k_{eff} is 1.0000 for all the cases.

Table 3 Calculated values of k_{eff} for UO_2-PuO_2 lattices

Case	No. of rods	HELIOS Single pin cell	k_{eff} Ref. 2 estimated	k_{eff} HELIOS-1.4 34-groups	$\|k_{eff}-1\|$ HELIOS-1.4 34-groups	k_{eff} HELIOS-1.6 45-groups	$\|k_{eff}-1\|$ HELIOS-1.6 45-groups
1	319	0.98295	0.9920	0.99240	0.00760	0.99041	0.00959
2	193	1.00083	0.9979	1.01221	0.01221	1.00990	0.00990
3	151	1.0071	0.9913	1.00542	0.00542	1.00318	0.00318
4	151	1.00459	0.9992	1.00030	0.00030	0.99804	0.00196
5	163	1.01446	0.9999	0.99805	0.00195	0.99623	0.00377
6	181	1.01003	0.9979	0.99831	0.00169	0.99658	0.00342
7	247	0.98583	0.9982	0.99651	0.00349	0.99384	0.00616
8	193	0.98555	0.9931	1.00787	0.00787	1.00536	0.00536
9	187	0.98037	1.0000	0.99615	0.00385	0.99385	0.00615
10	223	0.98637	0.9995	0.99832	0.00168	0.99672	0.00328

11	253	0.98002	0.9964	0.99678	0.00322	0.99509	0.00491
12	517	0.97147	0.9942	1.00978	0.00978	1.00796	0.00796
13	289	0.95577	0.9963	1.00254	0.00254	1.00022	0.00022
14	235	0.95554	0.9981	1.00776	0.00776	1.00558	0.00558
15	229	0.95319	1.0007	1.00189	0.00189	0.99990	0.00010
16	295	0.95444	0.9985	0.99772	0.00228	0.99626	0.00374
17	367	0.95939	0.9971	0.99372	0.00628	0.99246	0.00754
18	253	0.99165	0.9964	1.00185	0.00185	1.00030	0.00030
19	181	0.97826	0.9940	1.00209	0.00209	1.00010	0.00010
20	139	0.98481	1.0035	1.00941	0.00941	1.00072	0.00072
21	121	0.98018	1.0024	1.00578	0.00578	1.00366	0.00366
22	121	0.9808	1.0062	1.00342	0.00342	1.00173	0.00173
23	181	0.99043	1.0047	1.00393	0.00393	1.00257	0.00257
24	271	1.00549	1.0031	1.00486	0.00486	1.00378	0.00378
25	1489	0.99959	1.0035	1.00634	0.00634	1.00480	0.0048
26	830	0.98777	0.9988	1.00699	0.00699	1.00535	0.00535
27	484	0.97959	0.9988	0.99932	0.00068	0.99740	0.00260
28	421	0.9791	0.9968	1.00973	0.00973	1.00790	0.00790
29	457	0.98589	0.9971	0.99899	0.00101	0.99738	0.00262
30	487	0.98972	0.9989	0.99524	0.00476	0.99372	0.00628
avg.		**0.98404**	**0.99848**	**1.00212**	**0.00469**	**1.00003**	**0.00417**

As shown in Fig. 2, the k_{eff} of estimated critical cores for both cross-section libraries lie in the range of 0.99 to 1.01. Certainly, the effect of approximations and assumptions used in the code and uncertainties in physical parameters (such as axial buckling values, dimensions, and contents of lattice components) from the experiment exists in these results. However, their predictions agree better with the measured and estimated values than the single pin cell HELIOS results.

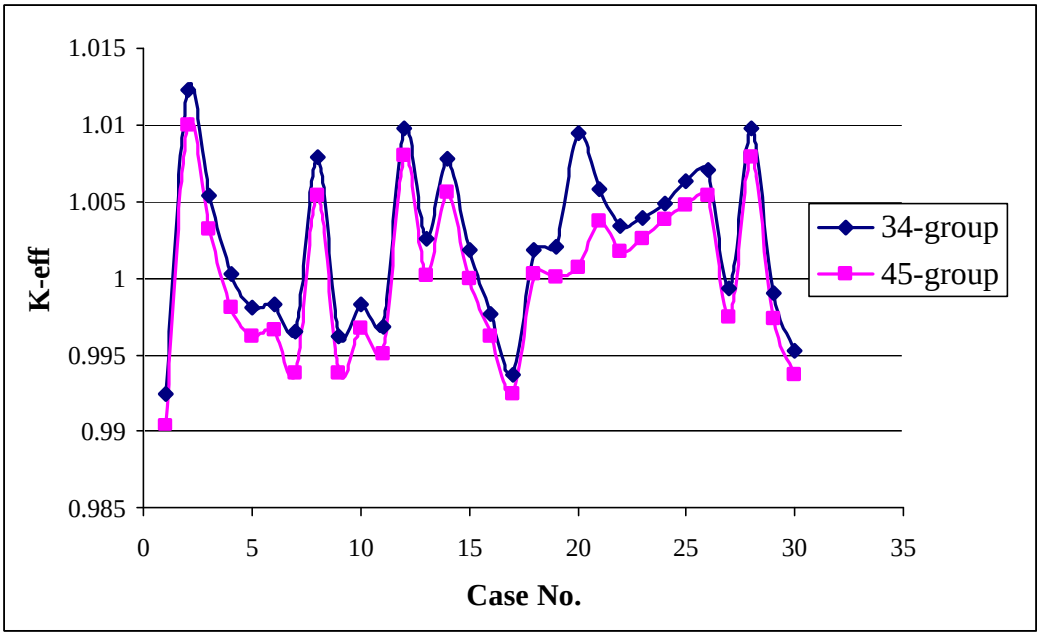

Fig. 2 k_{eff} values versus case no.

To illustrate further the above conclusion, a summary of average and standard deviation values is listed in Table 4. It can be seen that the 2D calculations produce better results than the single pin cell calculations, both per set and for all the 30 cases combined.

Table 4 A summary of averages and standard deviations

		Single Pin Cell	HELIOS-1.4	HELIOS-1.6
set 1 (1- 6)	average	1.00333	1.00112	0.99906
	stdv.	0.01101	0.00686	0.00670
set 2 (7-11)	average	0.98363	0.99913	0.99697
	stdv.	0.00315	0.00496	0.00484
set 3 (12-17)	average	0.95830	1.00224	1.00040
	stdv.	0.0068	0.00600	0.0057
set 4 (18-24)	average	0.98737	1.00448	1.00184
	stdv.	0.00949	0.00259	0.00154
set 5 (25-30)	average	0.98694	1.00277	1.00109
	stdv.	0.00755	0.00569	0.00566
all cases (1-30)	average	0.98404	1.00212	1.00003
	stdv.	0.01665	0.00528	0.00505

CONCLUSIONS

Using the published information concerning the MOX critical experiments HELIOS input decks were developed for modeling 30 cases of UO_2-PuO_2 lattices. The modeling approach involved developing an extrapolated critical core as a 2D problem of approximately cylindrical geometry for each case. The reflector region has been modeled explicitly and the axial buckling was used to account for the axial leakage. The calculated results compare well with the expected value (k_{eff} of unity) and are a significant improvement compared to single pin cell calculations that use a total buckling.

NOMENCLATURE

at%	percent isotopic abundance
B_g^2	geometrical buckling
B_z^2	axial buckling
k	current coupling order
k_{eff}	multiplication factor
wt%	weight percent
λ	reflector savings

Subscripts

eff	effective
g	geometry
z	axial

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