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HELIOS Verification Against High Plutonium Content Pressurized Water Reactor Critical Experiments

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Abstract

We present the results of HELIOS verification against VENUS PWR critical experiments loaded with high plutonium content mixed oxide fuels. The effective multiplication factors are calculated to be slightly supercritical within an acceptable error bound. In the prediction of power shape, HELIOS results are in close agreement with the measured values. The RMS errors of re-normalized calculated fission rate distributions are less than 1.4 % with either explicit or implicit models of micro tubes/rods in each fuel assembly for both ALL-MOX and GD-MOX mock-up cores.

1. Introduction

HELIOS[1] is a neutron and gamma transport code for lattice burnup, in general two dimensional geometry, which has been extensively qualified both by analyses of reactor physics experimental data[2] and by comparison with international benchmarks for lattice physics codes[3]. Our verification efforts so far have been mostly directed to the evaluation of criticality for UO_2 and MOX lattice cells. For commercial use of HELIOS code, it is also very important to verify the capability of calculating accurate spatial power distribution against representative critical experiments. There are few practical experimental data available for this purpose, one of which being VENUS PWR critical experiments. Since the verification carried out by ABB atom against KRITZ experiments[4] provides qualification for BWR-type cores, we focus in this study on the verification of HELIOS against VENUS PWR critical experiments loaded with high plutonium content mixed oxide (MOX) fuels.

2. VENUS Critical Experiments

Phase I of the VENUS International Program(VIP) PWR MOX fuel critical experiment[5] was completed last 1991 to obtain nuclear physics data for benchmark of nuclear design codes against high plutonium content MOX fuels in PWR type reactor. This program was performed under the coordination of Belgonucleaire using the VENUS critical facility located at SCK/CEN in Mol, Belgium.

VENUS critical cores consist of typical 17x17 PWR fuel assemblies, driver regions and water reflector regions. In the phase I, two mock-ups were investigated: ALL-MOX and GD-MOX mock-up. Table 1 gives the information about fuel pins. In the ALL-MOX mock-up core, a standard MOX assembly was loaded at the center of the core which was surrounded by four UO_2 fuel assemblies. In the GD-MOX mock-up core, the central MOX assembly was replaced with a MOX-gadolinium assembly. Therefore, the only difference between ALL-MOX and GD-MOX mock-up cores was the existence of 20 UO_2 fuel rods bearing Gd_2O_3 in the central assembly, which made the critical water level higher. For simulation of a hot-full-power (HFP) moderator condition, aluminum micro tubes and rods were inserted into MOX and 3.0w/o UO_2 fuel assemblies, respectively.

In each mock-up, the critical water level, reactivity effect of water level, axial bucklings, horizontal fission rate distribution and detector responses were measured. The horizontal rod-wise fission rate distribution was inferred from gamma scanning data. The axial bucklings were obtained from the cosine fitting of the axial fission rate which was also obtained by gamma scanning of some fuel rods.

3. HELIOS Calculation Model

In this verification, we used HELIOS version 1.4[1] combined with the 34 and 89 energy group library, hy941a, based on ENDF/B-VI. When modeling the VENUS critical cores, octant symmetry was assumed and specular boundary conditions, which are referred as reflective boundary conditions in other codes, was applied to the octant symmetric lines. Black boundary conditions were applied to the outside of water reflector, which is equivalent to the condition of no-return upon exit. We used 4 as the value of coupling coefficient specifying the angular representation of interface currents between structures. The measured axial bucklings were given region-wise. Since, however, HELIOS can not handle region-wise axial bucklings, the measured value at the central position of 3.0w/o UO_2 fuel assembly was used as the uniform axial buckling.

The fuel pin model consisted of the pellet and the cladding part. The thin film of air between the cladding and the pellet was included in the cladding material by homogenization, which means the cladding volume is increased but its density is reduced. The aluminum tubes and rods were modeled explicitly as well as implicitly in order to analyze neutron streaming effect referred in Ref. [6]. In the implicit model, the micro tubes and rods were smeared into water which resulted in 11 different water densities inside VENUS critical core. The Gd_2O_3 bearing fuel pins were modeled by dividing the fuel pellet into 8 radial rings so as to properly consider geometric self-shielding effect. Since the presence of detector reduces water volume in the central cell of the assembly which critically influences the power distributions of the neighboring fuel rods , it was modeled explicitly.

4. Results and Discussions

Two important reactor parameters, effective multiplication factor and horizontal fission rate distribution for some of the fuel pins, were calculated. Table 2 shows the effective multiplication factors calculated by HELIOS. The effective multiplication factors, in the case of using the 34 group neutron library, are 773 and 948 pcm greater than criticality in the explicit models of ALL-MOX and GD-MOX mock-up, respectively. However, by increasing the number of neutron group (89 neutron group library), the effective multiplication factor becomes closer to criticality. Considering HELIOS is a 2D code which can not accommodate region-dependent axial bucklings, these errors are within an acceptable error bound.

Table 3 and figure 1 show the summary of calculation errors in horizontal fission rate distribution. The absolute calculated values are underestimated in the MOX fuel assembly and UO_2 fuel assembly by 2% and 4% respectively, compared to the measured values. The underestimation in the absolute calculated values suggests application of revised fission yields of the Ba and La isotopes when inferring measured fission rate from gamma scanning data. Thus it is more meaningful to compare the re-normalized power shape for each fuel assembly. The last three columns of Table 3 and figure 1 show the RMS errors and relative errors of re-normalized fission rate distribution for each fuel assembly. The re-normalized power shapes are in close agreement between the calculations and measurements except Gd_2O_3 bearing fuel rods in which the fission rates were underestimated with a maximum error of 4.8%. The RMS errors of HELIOS calculations are within 1.4% with either explicit or implicit models of micro tubes/rods in each fuel assembly for both ALL-MOX and GD-MOX mock-up cores. The 3-4% underestimation of fission rates in Gd-pins could be partly explained by the difference of average fission rate ratio between MOX and UO_2 pins as shown in Table 3. If this difference is corrected (about 2%), that would leave a systematic underestimation of the Gd-pin fission rates by 0.7-1.7%. Reference 6 mentioned that streaming effects of the thermal neutron flow through aluminum micro tubes in the MOX fuel assembly was important enough to apply correction factors to the implicit model. But the HELIOS results with explicit and implicit models did not show any significant streaming effect to the contrary.

5. Conclusion

Through the verification against high plutonium content VENUS PWR critical experiments, it is shown that HELIOS can be used with confidence in calculating accurate spatial power distribution in PWR core intermixed with MOX and UO_2 fuel assemblies. HELIOS slightly overestimate criticality within an acceptable error bound. In the prediction of power shape, HELIOS results are in excellent agreement with the measured values. The RMS errors of re-normalized calculated fission rate distributions are less than 1.4% with either explicit or implicit models of micro tubes/rods in each fuel assembly for both ALL-MOX and GD-MOX mock-up cores.

6. References

1. HELIOS Users Manual, SCNADPOWER(1995)
2. HELIOS verification, Scandpower T3/41.16.10(1993)
3. "Multiple Recycling in Advanced Pressurized Water Reactors," Working Party on the Physics of Plutonium and Uranium Recycling, NEA/SEN/NSC(1996)
4. Verification of HELIOS against KRITZ BA-175 critical experiments," Scandpower A/S, BRA96-002(1996).
5. "VIP-PWR phase I Final Report", VIP-P92/10, SCK/CEN(Sept. 21,1992)
6. Masaaki Mori, et al.,"CASMO-4/SIMULATE-3 Benchmarking Against High Plutonium Content Pressurized Water Reactor Mixed-Oxide Fuel Critical Experiment," Nucl. Sci. and Eng. Vol. 121, 41-51(1995)

Table 1. Specifications of fuel pins

Fuel type	U^{235} Enrichment (w/o)	Pu content (w/o)	Gd_2O_3(w/o)	material of cladding
L-MOX	0.3	5.4	-	Zr-4
M-MOX	0.3	9.7	-	Zr-4
H-MOX	0.4	14.4	-	Zr-4
Gd-fuel	3.5	-	7.2	Zr-4
4.0w/o UO_2	4.0	-	-	AISI 304
3.0w/o UO_2	3.3	-	-	Zr-4
Al rod	-	-	-	Al
Al tube	-	-	-	Al

Table 2. Effective multiplication factor

Mock-up	micro tube/rod modeling	k_eff	number of groups of neutron library
ALL-MOX	Explicit	1.00773	34
		1.00604	89
	Implicit	0.99840	34
GD-MOX	Explicit	1.00948	34
	Implicit	1.00082	34

Table 3. Fuel rod fission rate distribution

Mock-up	micro tube/rod modeling	average fission rate ratio[a)]			RMS error [b)]		
		MOX	UO_2	Gd rods	MOX	UO_2	Gd rods
ALL-MOX	Explicit	0.98	0.96	-	1.037	0.976	-
	Implicit	0.99	0.95	-	0.844	0.991	-
GD-MOX	Explicit	0.98	0.96	0.95	1.393	0.973	3.637
	Implicit	1.00	0.96	0.97	1.225	1.013	2.681

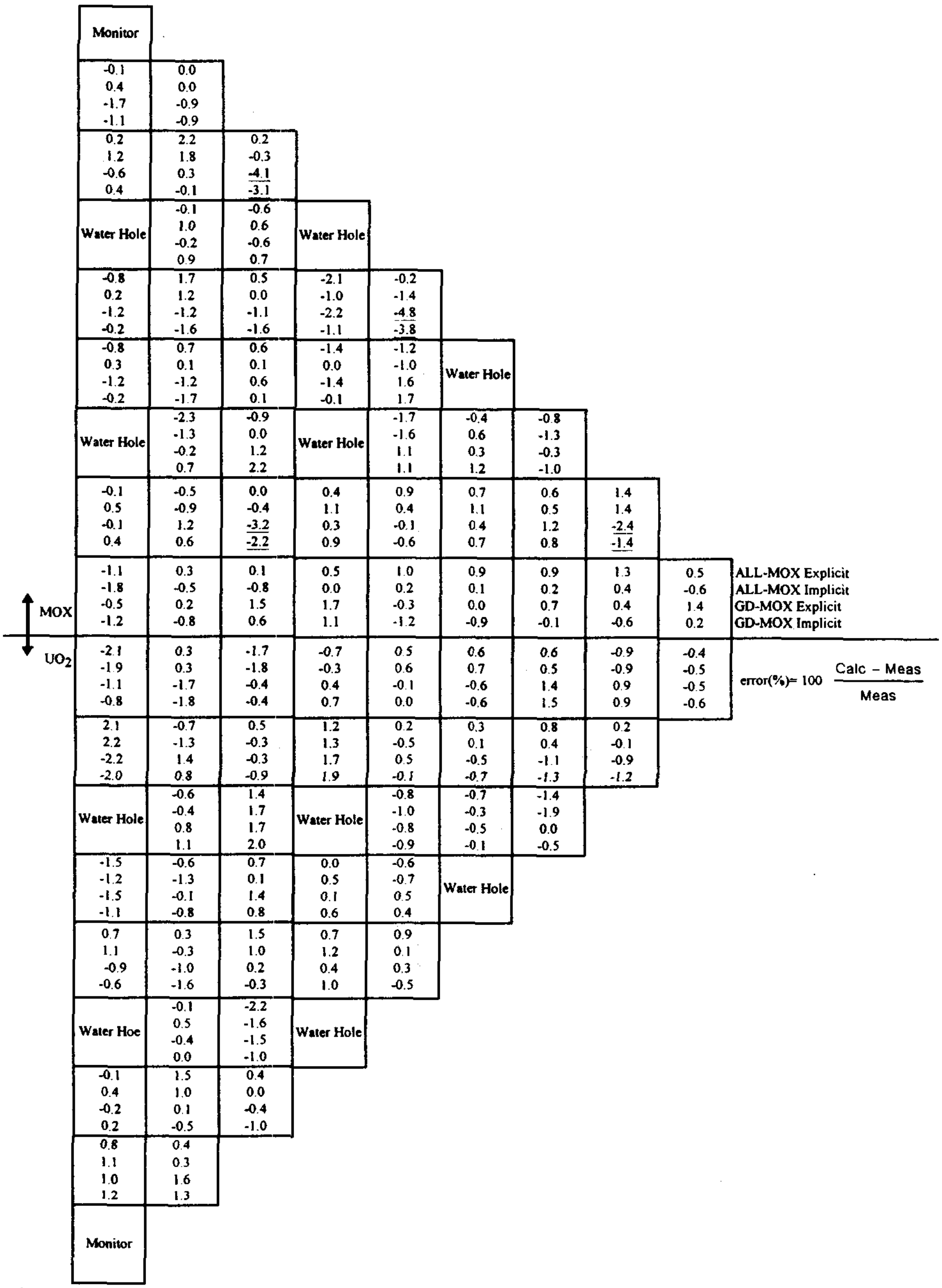
a) $\frac{1}{N}\sum_{i=1}^{N} F_i^H/F_i^M$

b) Root Mean Square of relative error(%) = $\sqrt{\frac{1}{N}\sum_{i=1}^{N}(100\times\frac{F_i^H-F_i^M}{F_i^M})^2}$

F_i^H = Calculated fission rate at i-th rod by HELIOS

F_i^M = Measured fission rate at i-th rod

N = Total number of rods per each fuel assembly



$$\text{error}(\%) = 100\ \frac{\text{Calc} - \text{Meas}}{\text{Meas}}$$

Monitor								
-0.1 0.4 -1.7 -1.1	0.0 0.0 -0.9 -0.9							
0.2 1.2 -0.6 0.4	2.2 1.8 0.3 -0.1	0.2 -0.3 -4.1 -3.1						
Water Hole	-0.1 1.0 -0.2 0.9	-0.6 0.6 -0.6 0.7	Water Hole					
-0.8 0.2 -1.2 -0.2	1.7 1.2 -1.2 -1.6	0.5 0.0 -1.1 -1.6	-2.1 -1.0 -2.2 -1.1	-0.2 -1.4 -4.8 -3.8				
-0.8 0.3 -1.2 -0.2	0.7 0.1 -1.2 -1.7	0.6 0.1 0.6 0.1	-1.4 0.0 -1.4 -0.1	-1.2 -1.0 1.6 1.7	Water Hole			
Water Hole	-2.3 -1.3 -0.2 0.7	-0.9 0.0 1.2 2.2	Water Hole	-1.7 -1.6 1.1 1.1	-0.4 0.6 0.3 1.2	-0.8 -1.3 -0.3 -1.0		
-0.1 0.5 -0.1 0.4	-0.5 -0.9 1.2 0.6	0.0 -0.4 -3.2 -2.2	0.4 1.1 0.3 0.9	0.9 0.4 -0.1 -0.6	0.7 1.1 0.4 0.7	0.6 0.5 1.2 0.8	1.4 1.4 -2.4 -1.4	
-1.1 -1.8 -0.5 -1.2	0.3 -0.5 0.2 -0.8	0.1 -0.8 1.5 0.6	0.5 0.0 1.7 1.1	1.0 0.2 -0.3 -1.2	0.9 0.1 0.0 -0.9	0.9 0.2 0.7 -0.1	1.3 0.4 0.4 -0.6	0.5 -0.6 1.4 0.2
-2.1 -1.9 -1.1 -0.8	0.3 0.3 -1.7 -1.8	-1.7 -1.8 -0.4 -0.4	-0.7 -0.3 0.4 0.7	0.5 0.6 -0.1 0.0	0.6 0.7 -0.6 -0.6	0.6 0.5 1.4 1.5	-0.9 -0.9 0.9 0.9	-0.4 -0.5 -0.5 -0.6
2.1 2.2 -2.2 -2.0	-0.7 -1.3 1.4 0.8	0.5 -0.3 -0.3 -0.9	1.2 1.3 1.7 1.9	0.2 -0.5 0.5 -0.1	0.3 0.1 -0.5 -0.7	0.8 0.4 -1.1 -1.3	0.2 -0.1 -0.9 -1.2	
Water Hole	-0.6 -0.4 0.8 1.1	1.4 1.7 1.7 2.0	Water Hole	-0.8 -1.0 -0.8 -0.9	-0.7 -0.3 -0.5 -0.1	-1.4 -1.9 0.0 -0.5		
-1.5 -1.2 -1.5 -1.1	-0.6 -1.3 -0.1 -0.8	0.7 0.1 1.4 0.8	0.0 0.5 0.1 0.6	-0.6 -0.7 0.5 0.4	Water Hole			
0.7 1.1 -0.9 -0.6	0.3 -0.3 -1.0 -1.6	1.5 1.0 0.2 -0.3	0.7 1.2 0.4 1.0	0.9 0.1 0.3 -0.5				
Water Hoe	-0.1 0.5 -0.4 0.0	-2.2 -1.6 -1.5 -1.0	Water Hole					
-0.1 0.4 -0.2 0.2	1.5 1.0 0.1 -0.5	0.4 0.0 -0.4 -1.0						
0.8 1.1 1.0 1.2	0.4 0.3 1.6 1.3							
Monitor								

Figure 1. Errors of re-normalized power distributions (under bar means the position of Gd rod)

(Both the measured and the calculated power distributions are normalized to unity inside each fuel assembly)