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VIPEX MOX Critical Experiment Simulation with HELIOS-1.6 and MCNP

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Abstract

A series of MOX critical experiments (VIPEX:VIP Extension) was performed at VENUS facility to provide the experimental core reactivity parameters; the decay effect of Pu-241 (americium effect), the control rod worth, and the effective beta in the first phase of VIPEX. In this paper, we have extended the qualification of the recent version of HELIOS-1.6 to the capability to predict the core reactivity parameters against the VIPEX MOX experiments as well the neutron multiplication factors and core power distribution. The effective multiplication factors calculated with HELIOS are in good agreement with experiments within the maximum discrepancy of 800pcm. Taking into account of HELIOS is a two-dimensional code which does not accommodate region-wise axial bucklings, these errors are considered within an acceptable error bound. The RMS error of HELIOS calculation for the power distribution is within 1.38% in MOX and UO_2 fuel assemblies. The americium effect, control rod worth, and b_{eff} from HELIOS calculation are in good agreement with measurements within the maximum errors of 6.4, 1.8, and 6.6%, respectively. The results show that HELIOS is qualified for an assembly code for practical PWR core design with MOX fuel.

1. Introduction

A series of MOX critical experiments (VIPEX:VIP Extension) was performed at VENUS facility to provide the experimental core reactivity parameters. The decay effect of Pu-241 (americium effect), the control rod worth, and the effective beta were measured in the first phase of VIPEX[1]. The capability of HELIOS[2] to predict the neutron multiplication factor and pin-wise power distribution had been verified against PWR critical experiments loaded with high plutonium content MOX fuels[3~6]. The reactivity parameters are also key parameters to characterize the neutronic behavior of the reactor core as well the neutron multiplication factor of core and power distributions. So, the nuclear core design method should be qualified whether it predicts the reactivity parameters well or not. In this paper, we have extended the qualification of the recent version of HELIOS-1.6[7] to the capability to predict the core reactivity parameters against the VIPEX MOX experiments.

2. Description of VIPEX MOX Experiments

The basic core configuration of VIPEX is identical to the previous VIP-PWR experiment[8] without gadolinium which consisted of a central 17x17 MOX fuel assembly surrounded with four 17x17 UO_2 fuel assemblies in a cross-like configuration as shown in Figure 1. For simulation of a hot-full-power (HFP) moderator condition of a commercial PWR at room temperature, aluminum micro tubes and rods were inserted into MOX and UO_2 fuel assemblies, respectively.

The MOX fuel rods used for the previous VIP-PWR experiment which was performed at about five-years earlier than VIPEX were also used for VIPEX experiment. A large number of Pu-241 nuclide was decayed to Am-241 during the five-years between VIP-PWR and VIPEX due to the short half-life of Pu-241[8]. The decay of Pu-241 changed the isotopic composition of MOX fuel rods resulting in the variation of core reactivity represented as americium effect. The negative reactivity insertion due to the americium effect was compensated by an increasing water level. The control rod worth was measured in subsequent steps. During each step, four control rods have been added or additional diver fuel rods have been loaded. The criticality of the core after inserting control rods or additional loading of driver fuels was maintained with water level control. The additional loading of driver fuel rods was to prevent the critical water level from being too high. In order to determine the delayed neutron fraction, two experimental methods were applied; the increase of the critical size and the prompt jump analysis and axial buckling methods. The aluminum tubes or rods were removed from the core in three steps to vary the moderator density for the measurement of moderator density effect. The critical water heights were reduced to compensate the insertion of core reactivity followed by the increase of moderator density.

During the experiments for reactivity parameter, the variations of core reactivity were compensated by controlling the water level for each configuration to be critical. So, the critical water level and the reactivity effect of water level change were measured for each configuration. The measured reactivity was deduced by multiplying the displacement of water level by the averaged reactivity effect of water level change between two core configurations.

3. Simulation of VIPEX Experiments

The HELIOS-1.6 was tested to simulate VIPEX critical experiment. An octant or a quarter symmetry was assumed in the HELIOS modeling of each configuration. As boundary conditions, a reflective and a black boundary conditions were applied to the symmetric lines and the outside of water reflector, respectively. 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. The aluminum micro tubes and rods were modeled. Since the presence of detector reduces water volume in the central cell of the assembly that critically influences the power distributions of the neighboring fuel rods, it was modeled explicitly. We used 4 as the value of current coupling order specifying the angular representation of interface currents between cells.

The measurement of axial buckling was carried out only for the basic core configuration and three core configurations for the measurement of moderator density effect. The axial buckling were measured region-wisely at the central positions of MOX and UO_2 fuel assemblies. Since HELIOS can not handle region-wise axial bucklings, MCNP calculations for all the core configurations were performed to determine the core-wise axial buckling in advance of HELIOS calculation. All the core configurations were simulated 2-dimensionally by using HELIOS with the axial bucklings from the MCNP calculations. Table I shows that the effective multiplication factors of each core configuration from MCNP and HELIOS calculations are in a good agreement with the experiments.

For the americium effect calculation, the isotopic compositions of MOX used for VIP-PWR were changed by taking into account of the decay of Pu-241. And then, two basic core configurations with different isotopic compositions of MOX were calculated with HELIOS. As described in Table 1, eight core configurations from CON-34-01 to CON-34-08 were the configurations for the control rod worth measurement. Driver fuel rods were additionally loaded in CON-34-02 and CON-34-07. The number of control rods in CON-34-06 was the same as that in CON-34-05. The difference between two configurations of CON-34-05 and CON-34-05 was the position of four control rods in MOX fuel region. So, the reference core configuration of CON-34-06 was not CON-34-05 but CON-34-04. The configurations CON-34-13 to CON-34-15 were constructed for the moderator density effect measurement. The aluminum tubes or rods in MOX fuel region were removed in CON-34-13. The aluminum tubes or rods were additionally removed from the part of UO_2 fuel region in CON-34-14, and all the rest of rods were removed in CON-34-15.

For the reactivity calculation with HELIOS for each core, the axial buckling leakage was kept to be zero, but the radial leakage was taken into account.

4. Results and Discussions

The effective multiplication factors were calculated with both the MCNP with ENDF/B-V and HELIOS-1.6 and summarized in Table I. The effective multiplication factors from MCNP calculation are in good agreement with experiments within the maximum discrepancy of 560pcm. The HELIOS results are also in good agreement with the experiment. The HELIOS two-dimensional calculation with axial buckling tends to slightly overestimate the neutron multiplication factor. Taking into account of HELIOS as a two-dimensional code which does not accommodate region-wise axial bucklings, these errors are considered within an acceptable error bound.

Figure 2 shows the RMS and relative errors of re-normalized fission rate distribution, which means both the measured and the calculated power distributions were normalized to unity in each fuel assembly. The RMS error of HELIOS calculation is within 1.38% in MOX and UO_2 fuel assemblies.

Table II shows the percent errors of HELIOS calculations for reactivity parameters. The americium effect, control rod worth, and b_{eff} from HELIOS calculation are in good agreement with measurements within the maximum errors of 6.4, 1.8, and 6.6%, respectively.

The results show that HELIOS is qualified for an assembly code for practical PWR core design with MOX fuel.

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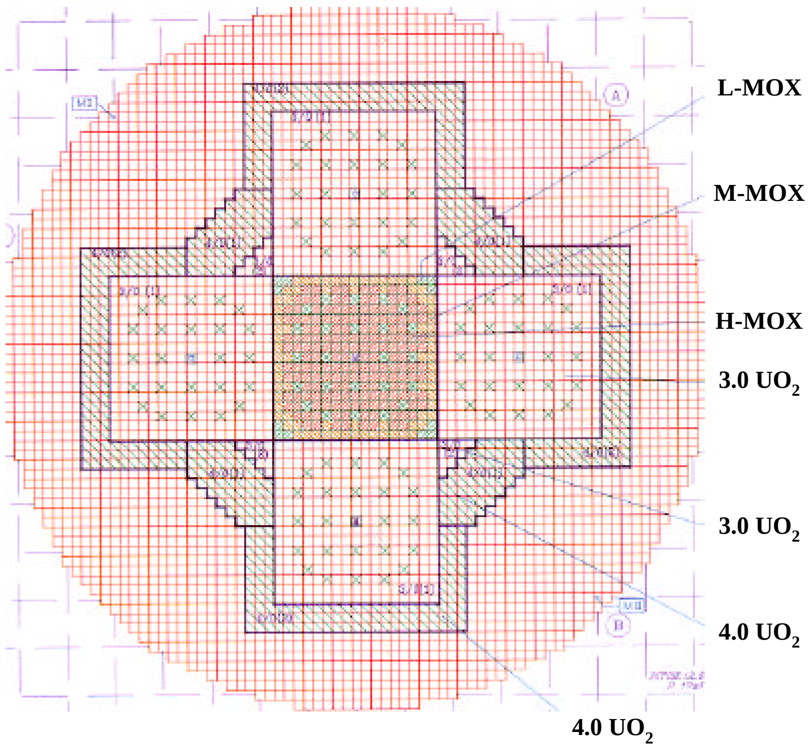

Figure 1. Configuration of VENUS core

Table I. Summary of effective multiplication factors calculation

Core Configuration	Description of Core Configuration	k_{eff} calculated	
		MCNP	HELIOS
CON-34-00	Basic configuration	0.99785±0.00049	1.00431
CON-34-01	4 control rod insertion to CON-34-00	0.99761±0.00057	1.00579
CON-34-02	Driver fuel addition to CON-34-01	0.99705±0.00046	1.00368
CON-34-03	Additional 4 control rod insertion to CON-34-02	0.99553±0.00045	1.00541
CON-34-04	Additional 4 control rod insertion to CON-34-03	0.99541±0.00044	1.00656
CON-34-05	Additional 4 control rod insertion to CON-34-04	0.99490±0.00046	1.00705
CON-34-06	Additional 4 control rod insertion to CON-34-04	0.99474±0.00049	1.00679
CON-34-07	Driver fuel addition to CON-34-06	0.99523±0.00048	1.00382

CON-34-08	Additional 4 control rod insertion to CON-34-04	0.99478±0.0006	1.00406
CON-34-09	Driver fuel addition to CON-34-00	0.99830±0.00048	1.00595
CON-34-10	Driver fuel addition to CON-34-09	0.99737±0.00049	1.00564
CON-34-11	Driver fuel addition to CON-34-10	0.99679±0.00049	1.00382
CON-34-12	Driver fuel addition to CON-34-11	0.99686±0.00047	1.00179
CON-34-13	Removal of aluminum rod in MOX region	0.99872±0.00051	1.00052
CON-34-14	Additional emoval of aluminum rod in UO_2 region	0.99860±0.00048	1.00726
CON-34-15	Additional emoval of aluminum rod in UO_2 region	1.00058±0.00050	1.00792

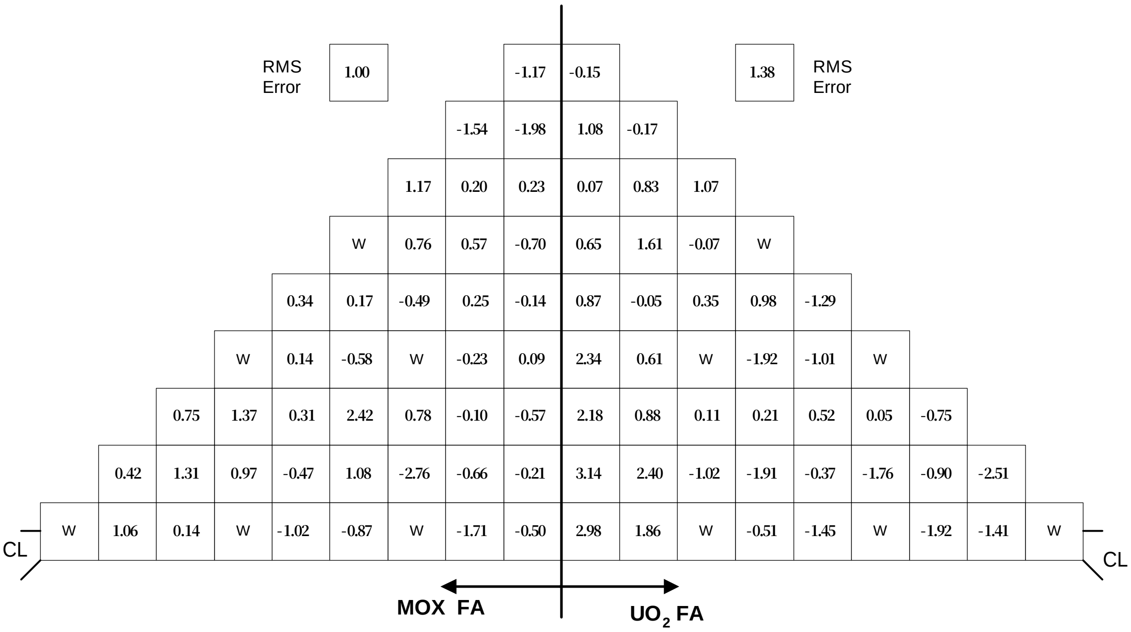

Figure 2. Configuration of VENUS core

Table II. Summary of reactivity parameter calculation

Reactivity Parameter	Description of Core Configuration	% error of calculate with HELIOS to experiment
Am-effect	VIP-PWR → VIPEX	– 6.4%
β_{eff}	-	+ 1.8%
Control Rod Worth	CON-34-00 → CON-34-01 CON-34-02 → CON-34-03 CON-34-03 → CON-34-04 CON-34-04 → CON-34-05 CON-34-04 → CON-34-06 CON-34-07 → CON-34-08	+ 3.3% + 6.5% + 6.6% + 0.9% + 1.4% + 3.6%