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Verification of HELIOS-MASTER System through Benchmark of Critical Experiments

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Abstract

The HELIOS-MASTER code system is verified through the benchmark of the critical experiments that were performed by RRC "Kurchatov Institute" with water-moderated hexagonally pitched lattices of highly enriched Uranium fuel rods (80w/o). We also used the same input by using the MCNP code that was described in the evaluation report, and compared our results with those of the evaluation report. HELIOS, developed by Scandpower A/S, is a two-dimensional transport program for the generation of group cross-sections, and MASTER, developed by KAERI, is a three-dimensional nuclear design and analysis code based on the two-group diffusion theory. It solves neutronics model with the AFEN (Analytic Function Expansion Nodal) method for hexagonal geometry. The results show that the HELIOS-MASTER code system is fast and accurate enough to be used as nuclear core analysis tool for hexagonal geometry.

1. Introduction

Two critical experiments with water-moderated hexagonally pitched lattices of highly enriched (approximately 80% U^{235}) fuel rods having cross-shaped cross-sections have been performed and evaluated in RRC "Kurchatov Institute"[1]. These cases consist of double lattices with boron carbide rods. Double lattices are two superimposed lattices of two different types of rods at different pitches. The fuel rod lattice pitch is 5.3mm for both experiments. The B_4C rod lattice pitches are 21.2 and 26.5mm, respectively. Both of these experiments are considered to be acceptable for use as a benchmark of critical experiments. This study describes the verification of the HELIOS-MASTER computer code system for the nuclear design and analysis of a hexagonal core through benchmark of these experiments. We also used the same input by using the MCNP[2] code that was described in the evaluation report[1], and compare our results with those of the evaluation report.

HELIOS[3,4,5], developed by Scandpower A/S, is a two-dimensional transport theory program for fuel burnup and gamma-flux calculation. It uses the cross-section library, which has 34 neutron groups and 18 gamma groups. This library has been obtained by condensation from the ENDF/B-VI based master library with 190 neutron groups and 48 gamma groups. MASTER[6] is a nuclear design and analysis code developed by KAERI and is based on the two group diffusion theory to calculate the steady-state and transient pressurized water reactor core in 3-dimensional Cartesian or hexagonal geometry. Its neutronics model solves the space-time dependent neutron diffusion equation with the analytic function expansion nodal method (AFEN) for hexagonal geometry[7,8,9]. The transverse leakage model is treated by a parabolic approximation, and the multi-level coarse mesh re-balancing and asymptotic extrapolation methods are implemented to accelerate the convergence of the iteration process. MASTER uses either macroscopic or microscopic cross sections provided by CASMO-3 or HELIOS.

2. Description of Experimental Configuration

Experiments were performed in a 15mm thick, open-top, stainless steel tank. The tank's inside diameter was 1600mm and its height was 2000mm. The top level of the tank coincided with the concrete floor of the experimental room. The tank support ring sat upon the concrete floor.

2.1 Reflector Region

The top water surface was at least 200mm above the top of the fuel region. The bottom water reflector was at least 500mm thick. The radial reflector was greater than 500mm thick. Therefore, all reflectors were effectively infinite. In the core, two 3mm thick aluminum alloy lattice plates fixed the fuel rods and B_4C rods. The bottoms of the fuel and B_4C rods were supported by a 13mm thick Plexiglas support plate. Between the fuel rod support place and bottom 20mm thick ADI aluminum alloy support plate was an 80mm square pitched lattice made of 20×20×20mm Plexiglas cubes. Figure 1 shows the axial schematic of the fuel and B_4C rods placement in the core.

2.2 Fuel Rod

The fuel rods had a "cross-shaped" cross section as shown in Figure 2. According to the fuel rod certificate, the fuel height was 700±20mm. According to measurements of 600 rods, the average fuel rod height was 705.0±6.7mm. The fuel rod cross section was twisted with 400mm period to form a spiral shape. The fuel rod end caps and clad were made of stainless steel. The caps had a diameter of 2mm. The bottom cap height was 22mm, and the top cap height was 20 to 62mm.

2.3 B_4C Rod

The B_4C rod tubes, plugs, and caps were made of stainless steel 0X16H15M3B. There were two types of B_4C rods, distinguished by their boron contents. The first type contained approximately 1.0 gram of natural boron, and the second type contained 3.5 grams of natural boron. Figure 3 shows the structural components of the B_4C rods.

2.4 Critical Configurations of the Double Hexagonal Lattices of Fuel Rods and B_4C Rods

Two critical configurations of hexagonally pitched double lattices with fuel rods and B_4C rods were assembled. The fuel rod lattice pitch values were 5.30±0.02mm for all experiments. The B_4C rod lattice pitch values were 21.2 and 26.5mm. The numbers of fuel and boron carbide rods for the two critical configurations are summarized in Table 1. Figures 4 and 5 give a view of the critical configurations with B_4C rod lattice pitch values of 21.2 and 26.5mm.

Table 1 Numbers of Fuel and B_4C Rods and Pitch Values for Critical Configurations

Case	Pitch of Fuel Rods (mm)	Pitch of B_4C Rods (mm)	B_{nat} Mass per Rod (g)	Number of Fuel Rods	Number of B_4C Rods
1	5.3	21.2	1.0	3460	217
2	5.3	26.5	3.5	4130	169

3. Description of HELIOS Model and Generation of Cross Sections

3.1 Fuel Region Geometry

Because the real geometry of the fuel rod used in the critical experiments could not be exactly reproduced, the cylindrical fuel rod having equivalent area was modeled in HELIOS. The difference in K_{eff} due to this effect was negligible according to Reference 1. The calculated fuel diameter and clad outer diameter were 3.30286mm and 3.93mm, respectively.

MASTER uses the space-time dependent neutron diffusion equation with the AFEN for hexagonal geometry to solve the neutronics model. The AFEN method, to speak briefly, represents neutron flux distribution in hexagonal node as analytic function expansion. If a node size is too small, the distribution of neutron flux in an actual node will be almost flat. Representing it in analytic function expansion, it can cause a numerical instability. Because the size of fuel rods used in the benchmark of critical experiments is actually too small (diameter: ~3.3mm), it is difficult to get the correct results if pin-by-pin modeling is used. To avoid this problem, a single homogenized fuel region was modeled, which included the fuel rods and B_4C rods in the core. MASTER calculates K_{eff} by using a macroscopic cross section, which is generated from HELIOS results in the homogenized fuel region. Because the configuration of core geometry for each case was composed of sextant symmetry, so was modeled the fuel region. The boundary condition for each plane was specular reflection. Figures 6 and 7 show the fuel regions modeled in HELIOS for each case, respectively.

3.2 Reflector Region Geometry

The reflector models of HELIOS consist of three categories; top, bottom and radial reflector. Because HELIOS is the two-dimensional transport theory program, it can’t directly describe top and bottom reflector models. In order to describe three-dimensional effects, a macroscopic cross section was extracted from the reflector region among the mixed region (Fuel + Reflector). The model of the top reflector corresponds to Figure 1 and consists of two layers;

1- 37mm mixed layer of top cap and water;
2- 300mm water layer.

The modeled top reflector is shown in Figure 8. The model of the bottom reflector also corresponds to Figure 1 and consists of five layers;

1- 22mm mixed layer of bottom cap and water;
2- 13mm Plexiglas support plate layer;
3- 20mm mixed layer (it consists of 80-mm square pitched lattice made of 20×20×20mm Plexiglas cubes immersed in water);
4- 20mm ADI aluminum alloy support plate layer;
5- 200mm layer of water.

Figure 9 shows the modeled geometry of the bottom layer in HELIOS. The radial reflector is modeled by a 300mm thick layer and is shown in Figure 10. The only difference between the two cases was the adjacent fuel region to each reflector region. The specular reflection boundary condition was used for each inclined plane and the vacuum boundary condition was used for the bottom plane.

3.3 Material Data

Nine materials were identified for each of the two experiments. The number densities of the fuel region and radial reflector were obtained from Reference 1. The number densities of mixture in the top and bottom reflector regions were calculated by their component ratio.

3.4 Temperature Data

The temperature of the critical assemblies varied in the range of 18°C to 20°C. In the model T=300K was used for all zones of the assemblies.

3.5 Generation of Cross Sections

In case of normal core design, MASTER at each burnup step uses microscopic cross section and heterogeneous form-functions such as pin power, pin burnup and fast and thermal flux generated by CASMO or HELIOS. Figure 11 shows the flowchart of the HELIOS-MASTER system. However it can only use macroscopic cross sections (Σ_{tr}, Σ_{cap}, Σ_{rem}, Σ_f,, Σ_f, $\kappa\Sigma_f$) for the evaluation of K_{eff} of the critical experiment. MASTER uses them as cross section library in the calculation of K_{eff}.

4. Results and Conclusion

Results of sample calculations are presented in Table 2. In cases of MCNP calculation, the results using the same method and input as presented in Reference [1] do not match exactly. This is caused by a difference in the cross section library used in MCNP run and machine environment, mainly, due to random number generation. The trend of results from HELIOS-MASTER between case1 and case2 is opposed to those from MCNP. Because, as shown in Figures 6 and 7, the HELIOS model of case2 contains the larger portion of water cell than that of case 1 in the fuel region, Σ_{tr} of case2 may be overestimated. In spite of modeling limitations described in the previous section, the results show that the HELIOS-MASTER code system is fast and accurate enough to be used as a nuclear core analysis tool for hexagonal geometry. To obtain statistically meaningful calculational uncertainty of the HELIOS-MASTER code system, additional benchmarking analysis is needed.

Table 2 Resultant K_{eff} of Sample Calculations

Code Case	MCNP4A[1)] (Difference)[2)]	MCNP4B (Difference)	HELIOS-MASTER (Difference)
1	0.9958±0.0015 (420±150 pcm)	0.9890±0.0011 (1100±110 pcm)	0.99971 (29 pcm)
2	1.0080±0.0015 (800±150 pcm)	1.0023±0.0011 (231±110 pcm)	0.99512 (488 pcm)

1) Results obtained from Reference 1.

2) Values in parenthesis are $|\text{Critical} - \text{Calculate}|$.

5. Acknowledgement

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6. References

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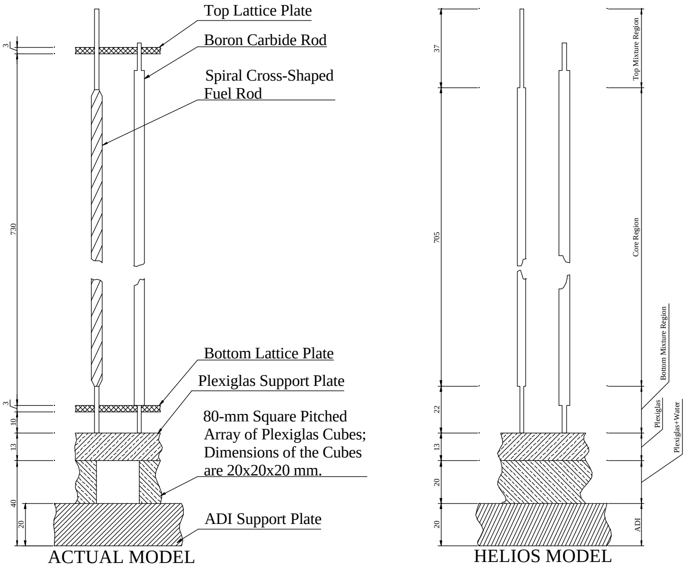

Figure 1 Schematic of the Fuel and B_4C Rods Placement in the Core (dimensions given in mm)

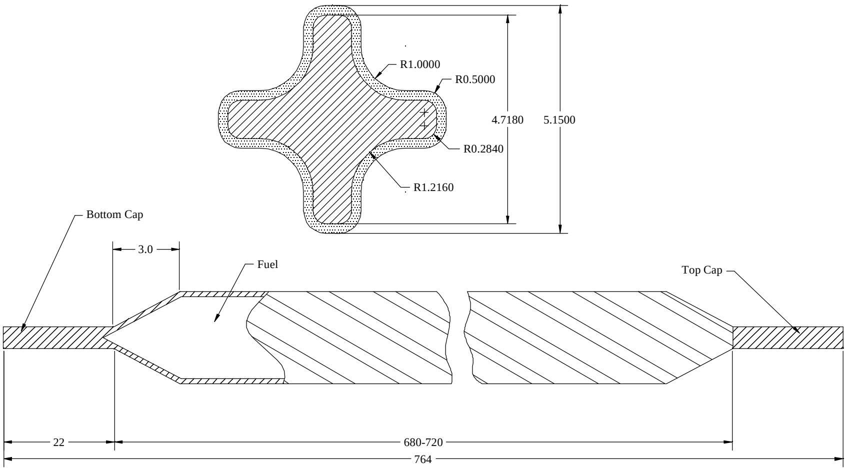

Figure 2 Spiral Cross-Shaped Fuel Rod (dimensions given in mm)

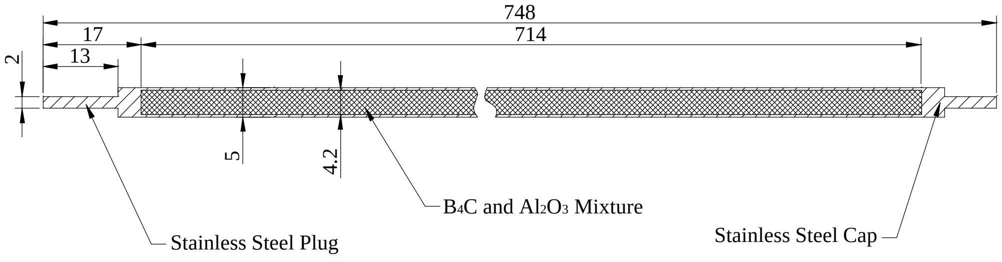

Figure 3 B_4C Rod (dimension given in mm)

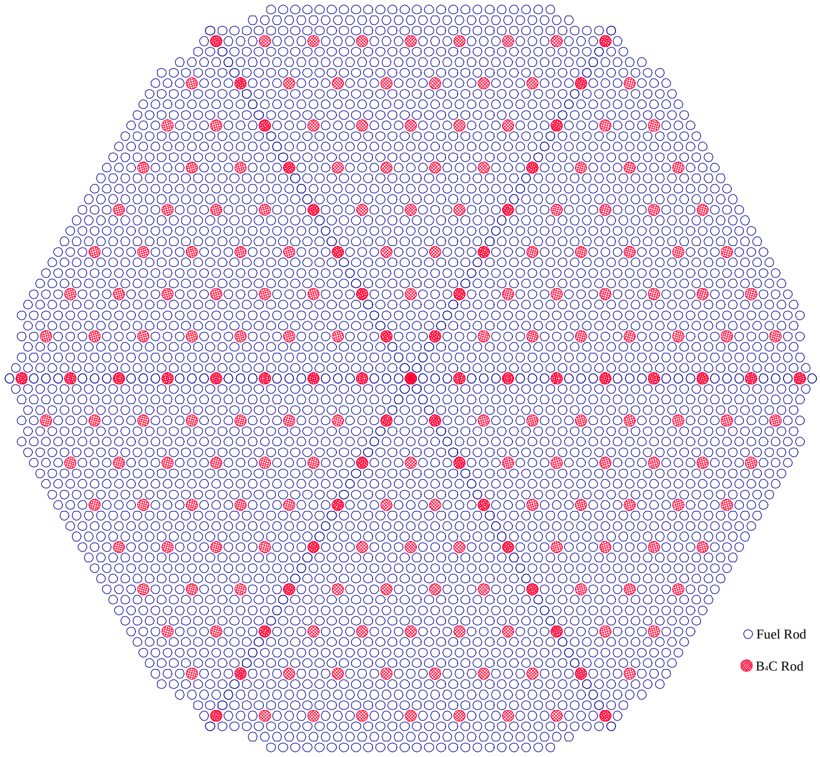

Figure 4 Critical Configuration of the First Double Lattice with Fuel and B_4C Rods
(Fuel rod lattice pitch value is 5.3mm; B_4C rod pitch value is 21.2mm)

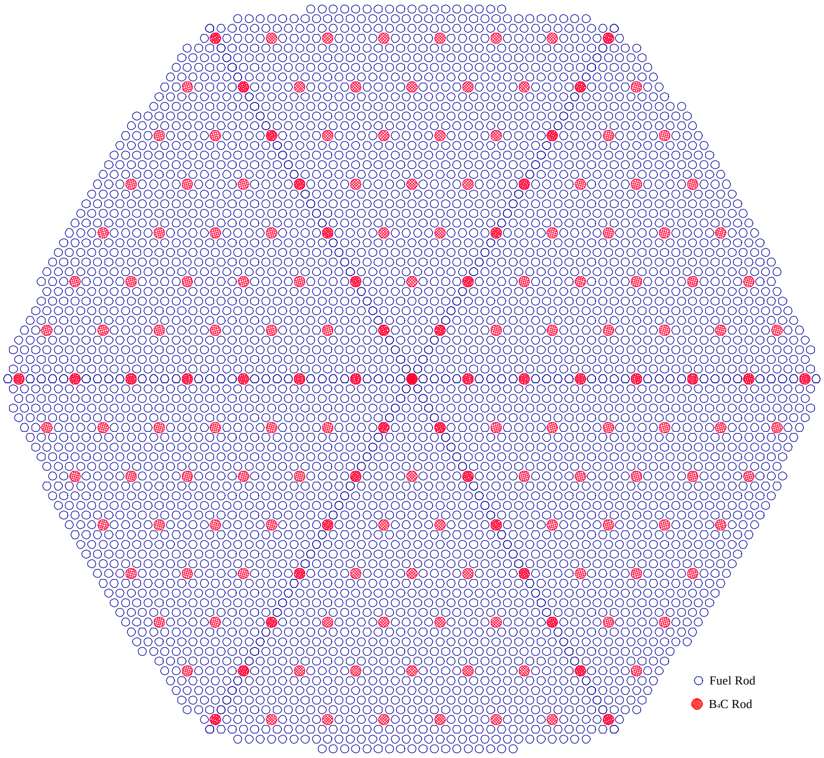

Figure 5 Critical Configuration of the Second Double Lattice with Fuel and B_4C Rods
(Fuel rod lattice pitch value is 5.3mm; B_4C rod pitch value is 26.5mm)

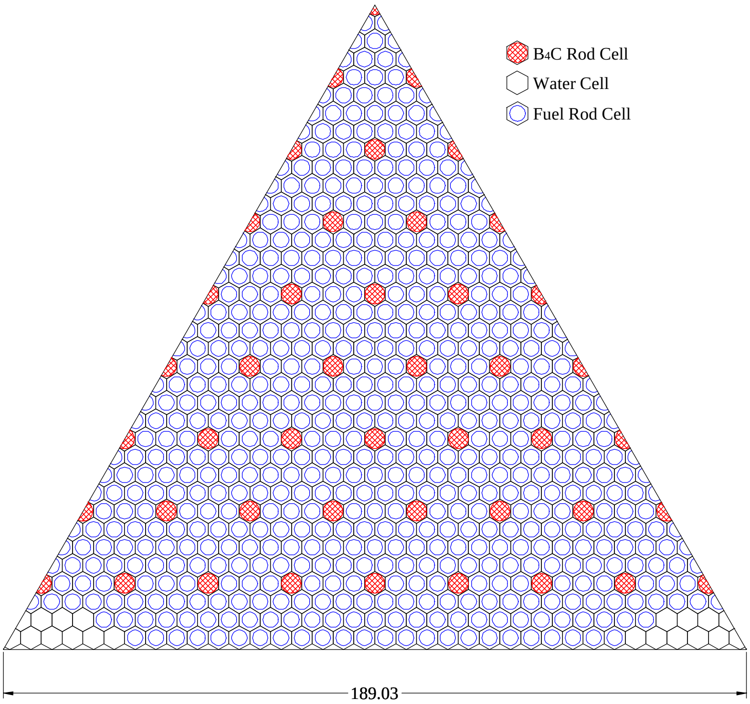

Figure 6 Fuel Region in Case1 HELIOS Model (dimensions given in mm)

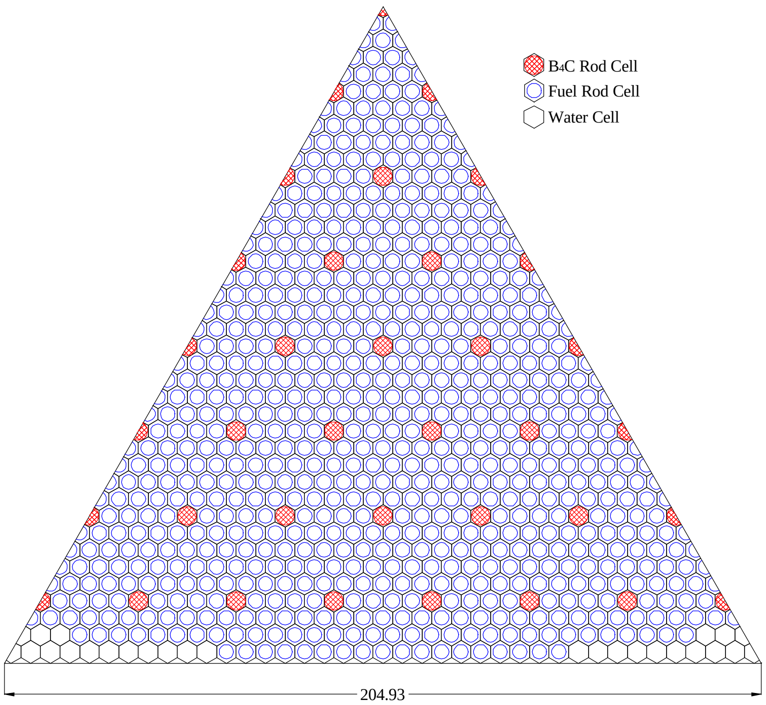

Figure 7 Fuel Region in Case2 HELIOS Model (dimensions given in mm)

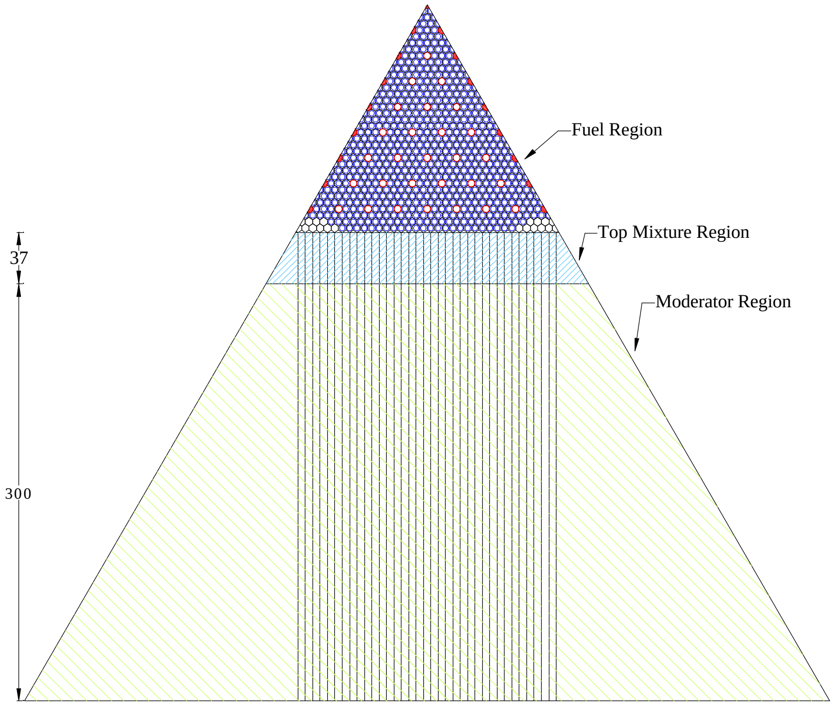

Figure 8 Top Reflector Modeled in HELIOS (dimensions given in mm)

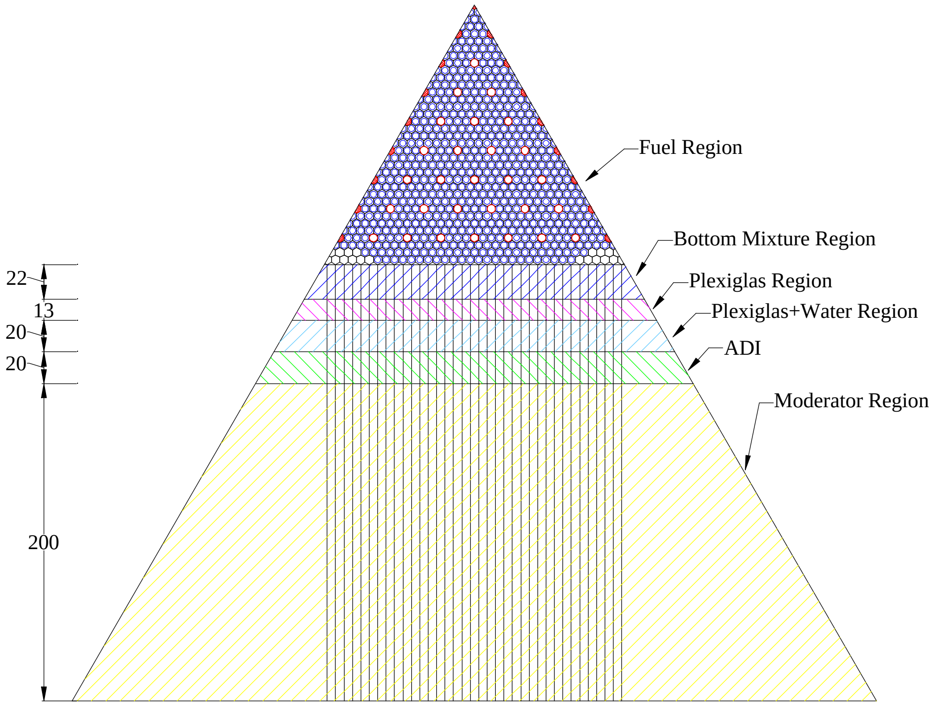

Figure 9 Bottom Reflector Modeled in HELIOS (dimensions given in mm)

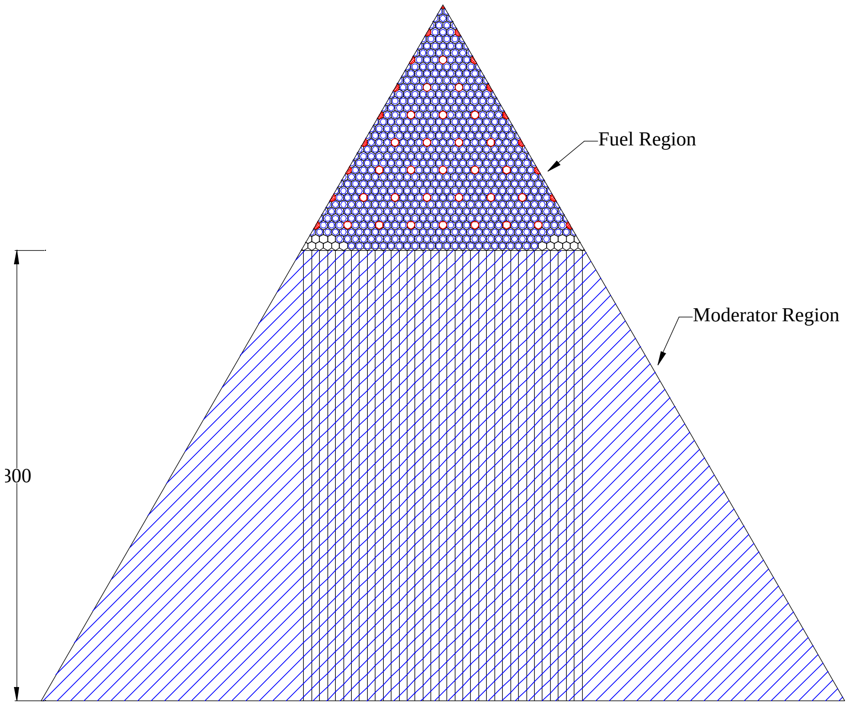

Figure 10 Radial Reflector Modeled in HELIOS (dimensions given in mm)

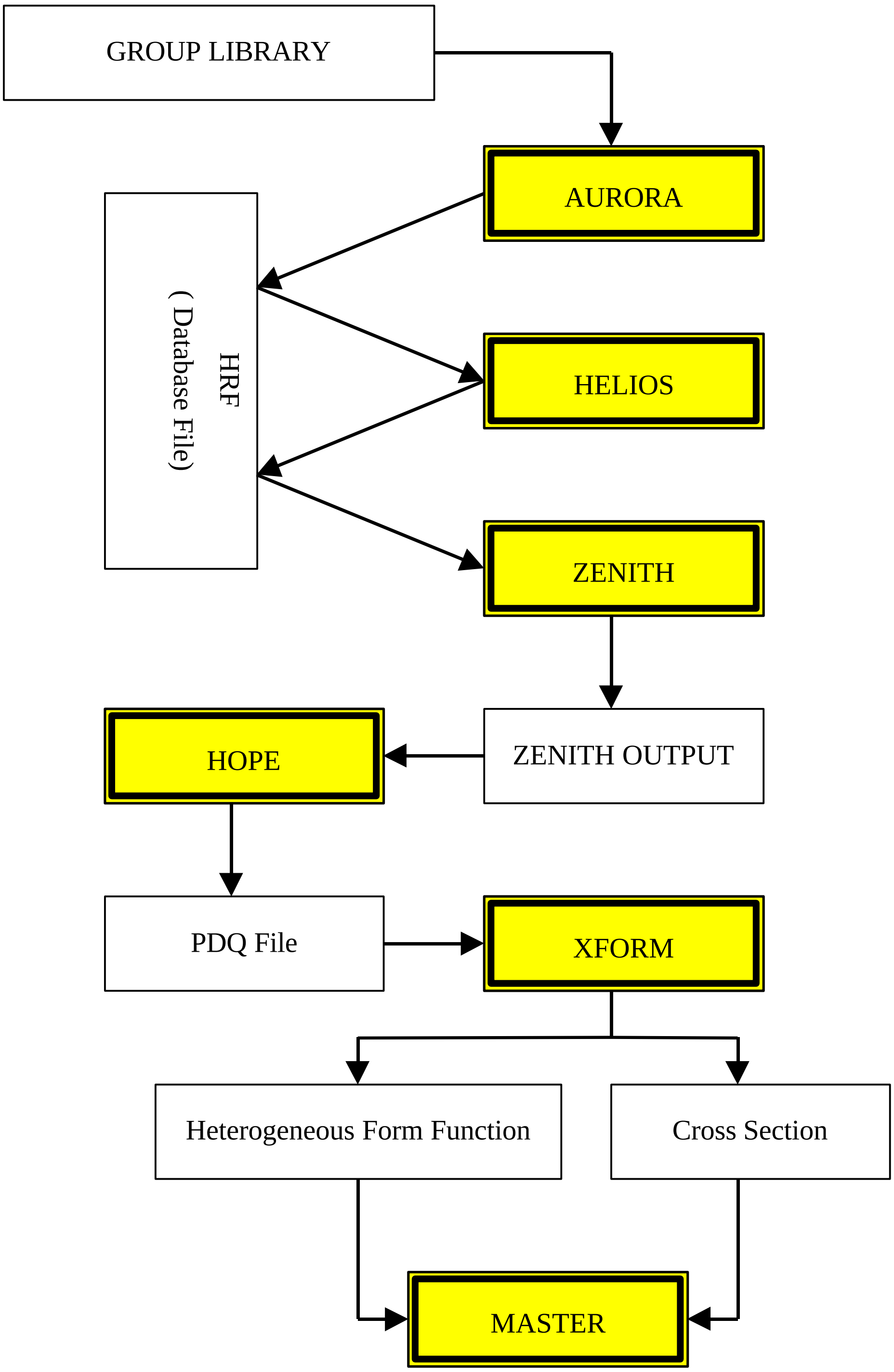

Figure 11 Flowchart of HELIOS-MASTER System