Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 10-11, 2007

Application of HELIOS to Compact Nuclear Power Source Numerical Benchmark

Hyung-Kook Joo
Korea Atomic Energy Research Institute, 150 Deokjin-dong, Yuseong, Deajeon, Korea; hkjoo@kaeri.re.kr

1. Introduction

Numerical benchmark problems based on the Compact Nuclear Power Source (CNPS) experiments [1,2,3] have been recently specified for the validation of neutronic data and codes developed for the analysis of Very High Temperature Reactor (VHTR) cores.[4] For the numerical benchmark, the original configurations of the CNPS core that used irregular cylindrical arrangements of channels were transformed into those with regular Cartesian geometry arrangements of channels for the purpose of simplifying the geometry for deterministic code calculations. Preserving the CNPS core physics characteristics was a requirement for this transformation. Using this approach, 2-D and 3-D benchmark cases have been defined for two critical configurations of the CNPS that have 184 and 492 fueled channels, respectively. The parameters to be calculated and compared for the benchmark cases were the eigenvalue, axial and radial power distributions, and shim and control rod worths.

The specified numerical benchmark cases have been analyzed using deterministic two-step calculations with lattice and whole-core analysis codes, HELIOS and DIF3D, respectively. The k_{eff} values were calculated by using HELIOS/DIF3D with various energy group cross sections from different spectrum environment. The power distributions and reactivity parameters were calculated using HELIOS/DIF3D with 47-group cross sections and found to be in good agreement with those obtained with MCNP.

2. Description of CNPS Experiments and Numerical Benchmark

2.1 CNPS Core and Experiments

The CNPS core was reflected both radially and axially with graphite. The core contained 492 fuel channels, 5 control rod channels, and 12 heat pipe channels as depicted schematically in Figure 1. Different critical configurations were obtained by loading different number of fuel channels with uncladded fuel compacts containing the TRISO fuel particles in a graphite matrix; low-enriched uranium oxy-carbide fuel was used (19.9% U-235). The requirement of ensuring a minimum web thickness between any two free surfaces made it difficult to maintain a constant fuel element pitch. To minimize this problem, the fuel channels were arranged in an irregular lattice with a 45-degree azimuthal symmetry. The active core height was 108.46 cm, which is less than the height of the core block (113 cm).

Critical state measurements were conducted under the CNPS experimental program. Four of the critical loadings contained 184, 202, 380, and 492 fueled channels. [1] In addition, experiments were performed to determine material worths, safety rod worths, shim differential worths, temperature reactivity coefficients, and power profiles.

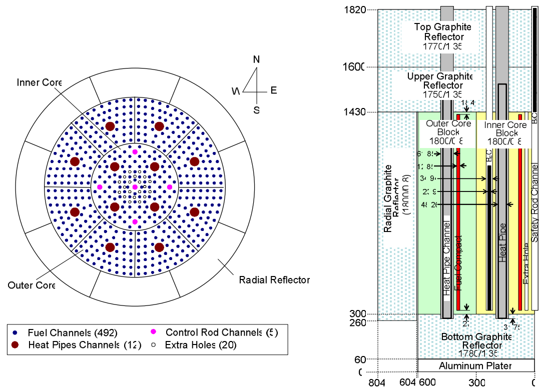

Figure 1. Planar and Vertical Views of CNPS Core.

2.2 Numerical Benchmark Based on CNPS

The numerical benchmarks based on the CNPS experiments have been specified for two cases: 184 fueled-channel core (CNPS-184) and 492 fueled-channel core (CNPS-492). The CNPS-184 configuration is composed of 184 fuel cells, one empty safety rod channel cell at the center of core, four empty control rod channel (including one empty shim rod channel) cells, twelve empty heat pipe channel cells, 308 graphite cells with empty fuel channel, and 404 graphite reflector cells as shown in Figure 2. The CNPS-492 configuration is composed of 492 fuel cells, one empty safety rod channel, three control rod channels and one shim rod channel in symmetric positions, twelve heat pipe channels, and 404 graphite reflector cells. Each cell in both the CNPS-184 and CNPS-492 cores has a square shape. The side length of each square cell is 4.7138 cm. For the axial configuration of the 3-D benchmark problem, a top graphite reflector, a bottom aluminum platen and a bottom graphite reflector are included in the configuration. In the CNPS-492 core configuration, three control rods and one shim rod are partially inserted. The control rod and shim rod in 2-D benchmark for CNPS-492 core are axially homogenized by diluting the number density of B_4C. The radial reflector, axial reflector, and aluminum platen cells have a solid square cell without channel.

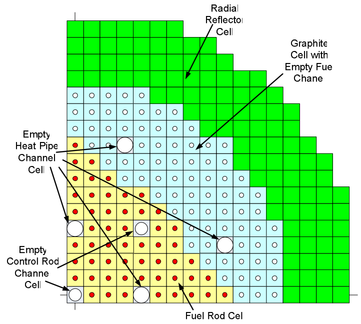

Figure 2. Benchmark Configuration of 184 Fueled-Channel Core

For the fuel cell, the homogeneous fuel compact model only is given in this paper. Even though the particle fuel model was also specified in the benchmark[6], the particle heterogeneity effect for this benchmark was small due to the high moderator-to-fuel ratio and high fuel packing fraction. Reference 1 also reported that the reactivity effect of grain shielding (heterogeneity effect) was calculated by General Atomics Technologies to be on the order of 200 to 300 pcm.

The parameters to be calculated and compared for the benchmark cases are the k_{eff} value, axial and radial power distributions, and shim and control rod worths.

3. Results of Benchmark Calculations

Deterministic calculations using lattice and whole-core analysis codes have been performed for the CNPS numerical benchmark cases. The lattice calculations were done with the HELIOS code using the 47-energy-group library. The results of the lattice calculations have been used to generate homogeneous cell cross section data for DIF3D calculations. Whole-core DIF3D results have been obtained using the 8, 20, and 47-group cross-sections obtained from HELIOS calculations. The DIF3D calculations using both the DIF3D-VARIANT (nodal transport) and DIF3D-nodal (nodal diffusion) options have been performed. The k_{eff} values calculated with DIF3D with 47-group cross section for the 2-D and 3-D benchmark cases, the VARIANT results with P-1, P-3, and P-5 angular flux approximations and the DIF3D-nodal results, are summarized and compared with the reference MCNP4C results in Table I. The highest order HELIOS/DIF3D 47-group calculation (P-5) gives k_{eff} values that are within 0.4% of the MCNP results for both the 184 and 492 fueled-channel cores. Twenty-group and eight-group HELIOS/DIF3D calculations were also performed for the 2-D benchmark case. Since the energy group structure for the 8-group calculation is not optimized for this CNPS case, it shows 0.4~0.7 *%Δk* difference from that of the 47-group calculation.

The radial power distributions calculated by HELIOS/DIF3D also agree well with those from MCNP calculations; the RMS error is 0.25 % for the 184 fueled-channel core and 0.81% for the 492 fueled-channel core.

Table I. k_{eff} Values of Deterministic Calculations for CNPS Benchmark

			184 Fueled-channel Core	492 Fueled-channel Core
2-D Core	MCNP4C (with Homogeneous Fuel Compact Model)		1.19555	1.15799
	HELIOS/DIF3D (47-g)	Nodal Diffusion	1.19717	1.14622
		VARIANT P-1	1.19547	1.14470
		VARIANT P-3	1.19928	1.15348
		VARIANT P-5	1.19965	1.15484
3-D Core	MCNP4C (with Homogeneous Fuel Compact Model)		1.00164	1.00378
	HELIOS/DIF3D (47-g)	Nodal Diffusion	1.00387	0.99319
		VARIANT P-1	1.00235	0.99181
		VARIANT P-3	1.00897	1.00167
		VARIANT P-5	1.00977	NA

4. Conclusion

The specified numerical benchmark cases have been analyzed using deterministic two-step calculations with lattice and whole-core analysis codes, HELIOS and DIF3D, respectively. The k_{eff} values and the power distributions calculated using HELIOS/DIF3D were found to be in good agreement with those obtained with MCNP4C as reference solutions. The material worths calculated by the deterministic code package were also in good agreement. It was also found that considerable transport effects exist in these benchmark cases, particularly for the CNPS-492 2-D core and the 3-D cores of the CNPS-184-and CNPS-492 cases. The results of the benchmark calculations with the deterministic codes show that the numerical benchmark cases are reasonably specified.

ACKNOWLEDGEMENTS

This work was supported by the Argonne National Laboratory.

REFERENCES

[1] G. E. Hansen and T. G. Palmer, "Compact Nuclear Power Source Critical Experiments and Analysis," *Nucl. Sci. Eng.*, **103**, pp.237-246, 1989.
[2] R. G. Palmer, "Postanalysis of the CNPS Critical Experiments," Proc. Int'l. Reactor Physics Conference, Jackson Hole, Wyo., 18 September 1988.
[3] G. E. Hansen, J. H. Audas, E. R. Martin, R. A. Pederson, G. D. Spriggs, and R. H. White, "Critical Experiments in Support of the CNPS Programs," Proc. Int'l. Reactor Physics Conference, Jackson Hole, Wyo., 18 September 1988.
[4] H.K.Joo, T. A. Taiwo, and W. S. Yang, "VHTR Numerical Benchmark Based on the Compact Nuclear Power Source Experiments," Proc. M&C+SNA 2007 Monterey, California, USA, April 15-19, on CD-ROM, American Nuclear Society, Lagrange Park, IL. 2007.