NECP-CACTI: Pressurized Water Reactor Lattice Code Development

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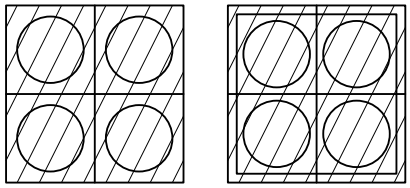
INTRODUCTION

As one of the key components of nuclear reactor-related software for power plants, the status of Pressurized Water Reactor (PWR) lattice code indicates the nuclear power development of the corresponding country. Hence, Nuclear Engineering Computational Physics Lab. (NECP) developed the PWR lattice code NECP-CACTI[1]. Currently, it contains several modules including multi-group data library NECL1.0 with both 69 and 172 energy groups, self-shielding cross section module which adopts sub-group method, transport calculation based on modular MOC method[2-3], depletion calculation using the traditional predictor-corrector (PC), projected predictor-corrector (PPC) and logarithm linear reactivity (LLR) methods. Beyond that, the lattice code realizes the leakage correction calculation and restart calculation.

Three main works based on NECP-CACTI are summarized here. Firstly, it adopts Lattice Modular MOC to describe clearly the water gap between the lattices. Secondly, it divides total energy release into direct fission energy and indirect capture energy in order to calculate pin power and depletion of burnable poison Gadolinium. Thirdly, it adopts 172-energy-group structure to calculate effective shielding cross section of isotope Plutonium in order to calculate MOX fuel.

LATTICE WITH WATER GAP

Lattice Modular MOC is employed in NECP-CACTI as neutron transport solver, making the lattice code NECP-CACTI can deal with the water gap between the lattices exactly which overcomes the shortage of Cell Modular MOC with the treatment of the water gap. The difference between Cell and Lattice Modular MOC is shown in Fig. 1. A traditional pressurized water reactor lattice with water gap flux distribution is given in Fig. 2. Case 1 and Case 2 respectively refer to Lattice and Cell Modular MOCs as neutron transport solver.



Cell Modular Lattice Modular

Fig. 1 Modular MOC Ray-Tracing

As shown in Fig. 2, Cell Modular MOC overestimates flux inner the lattice while underestimates flux outer the lattice. It means that the approximate calculation method employed by traditional Cell Modular MOC changes the shape of the flux distribution in Lattice. But the maximum relative error can be reduced from -0.26% to -0.08% by adopting Lattice Modular MOC transport solver.

1.0056								
1.0065								
1.0039								
0.17%								
0.26%								
1.0017	1.0007							
1.0026	1.0016							
1.0014	0.9997							
0.02%	0.10%							
0.12%	0.19%							
1.0015	1.0008	1.0010						
1.0024	1.0017	1.0019						
1.0010	1.0003	0.9997						
0.05%	0.05%	0.13%						
0.14%	0.13%	0.22%						
1.0055	1.0020	1.0017	1.0054					
1.0063	1.0027	1.0024	1.0061					
1.0040	1.0020	1.0023	1.0040					
0.15%	0.00%	-0.06%	0.14%					
0.23%	0.07%	0.01%	0.21%					
1.0013	1.0004	1.0010	1.0028	1.0021				
1.0020	1.0011	1.0017	1.0034	1.0026				
1.0022	1.0003	1.0002	1.0030	1.0017				
-0.09%	0.00%	0.08%	-0.02%	0.04%				
-0.02%	0.07%	0.14%	0.04%	0.09%				
1.0020	1.0009	1.0012	1.0026	1.0026	1.0030			
1.0026	1.0014	1.0017	1.0031	1.0030	1.0032			
1.0014	1.0005	1.0003	1.0029	1.0025	1.0032			
0.06%	0.04%	0.09%	-0.03%	0.01%	-0.02%			
0.12%	0.09%	0.14%	0.02%	0.04%	0.00%			
1.0033	1.0007	1.0011	1.0039	1.0013	1.0006	0.9987		
1.0036	1.0009	1.0013	1.0041	1.0013	1.0005	0.9983		
1.0028	1.0015	1.0013	1.0030	1.0012	1.0005	0.9977		
0.05%	-0.08%	-0.02%	0.09%	0.01%	0.01%	0.10%		
0.08%	-0.06%	0.00%	0.11%	0.01%	0.00%	0.06%		
1.0006	0.9990	0.9990	1.0001	0.9981	0.9975	0.9963	0.9959	
1.0005	0.9988	0.9982	1.0003	0.9977	0.9969	0.9955	0.9947	
0.9998	0.9991	0.9989	0.9999	0.9981	0.9975	0.9960	0.9962	
0.08%	-0.01%	0.01%	0.02%	0.00%	0.00%	0.03%	-0.03%	
0.07%	-0.03%	-0.07%	0.04%	-0.04%	-0.06%	-0.05%	-0.15%	
0.9985	0.9976	0.9977	0.9984	0.9969	0.9967	0.9959	0.9949	0.9956
0.9980	0.9970	0.9970	0.9978	0.9962	0.9958	0.9947	0.9931	0.9936
0.9985	0.9981	0.9980	0.9984	0.9968	0.9969	0.9958	0.9957	0.9959
0.00%	-0.05%	-0.03%	0.00%	0.01%	-0.02%	0.01%	-0.08%	-0.03%
-0.06%	-0.11%	-0.10%	-0.06%	-0.06%	-0.11%	-0.11%	-0.26%	-0.23%

Case 1: Lattice modular MOC calculation result
Case 2: Cell modular MOC approximate calculation result
MCNP: MCNP calculation result
Error 1: Relative error between CASE1 and MCNP
Error 2: Relative error between CASE2 and MCNP

Fig. 2 One-group flux distribution of a 1/8 PWR lattice

LATTICE WITH GADOLINIUM

Usually, the total energy release per fission for fissionable nuclide *i* is:

$$\kappa_i = W_{\text{fiss},i} + W_{\text{n},i} + (\nu_i - 1)Q \tag{1}$$

where $W_{\text{fiss},i}$ is direct fission energy, $W_{\text{n},i}$ is mean incoming neutron energy, ν_i is mean values of the number of neutrons emitted per fission. Q is an additional term accounting for the indirect energy from capture gammas and decay energy of capture products[4]. Q is usually the mean reference value 5.991MeV or 6.1MeV. CASMO-4[5] and HELIOS[6] use 5.991MeV/capture, while WIMS-D[7] uses 6.1MeV/capture.

Therefore, macroscopic energy release cross section is defined as:

$$\kappa\Sigma_{\text{f},ig,imat} = \sum_{i\in imat} \kappa_i N_i \sigma_{\text{f},i,ig} \tag{2}$$

However, the mean reference value Q does not account for capture energy of isotope Gadolinium, introducing error in macroscopic energy release cross section with burnable poison Gadolinium.

In lattice code NECP-CACTI, the total energy release per fission for fissionable nuclide i is defined as:

$$\kappa_i' = W_{\text{fiss},i} + W_{\text{n},i} \tag{3}$$

and the macroscopic energy release cross section is defined as:

$$\kappa\Sigma'_{\text{f},ig,imat} = \sum_{i\in imat} \kappa_i' N_i \sigma_{\text{f},i,ig} + \sum_{i\in imat} q_i N_i \sigma_{\text{c},i,ig} \tag{4}$$

where N_i is the nuclide density of nuclide i in material $imat$, q_i is the capture energy of nuclide i in material $imat$, $\sigma_{\text{f},i,ig}$ is the microscopic fission cross section of nuclide i in material $imat$ and energy group ig, $\sigma_{\text{c},i,ig}$ is the microscopic capture cross section of nuclide i in material $imat$ and energy group ig.

The macroscopic energy release cross section is not required by neutron transport calculation. However, it is a key component in pin power distribution with burnable poison Gadolinium and depletion calculations. Because the macroscopic energy release cross section determines the burnup rate. Thus, macroscopic energy release cross section can be obtained according to the definitions above.

NECP-CACTI adopts Eq. (4) to calculate macroscopic energy release cross section for power distribution and depletion calculation. Fig. 3 shows the power distribution of a lattice with burnable poison Gadolinium pin using DAYA BAY plant data[8]. Reference solution is given by the lattice code APOLLO. Pin power is calculated by CASMO4 and NECP-CACTI separately. The relative errors of pin power with burnable poison Gadolinium from NECP-CACTI are -5.33% and -6.04% respectively, but -65.76% and -65.12% from CASMO4. Fig. 4 is the depletion calculation result of the above lattice. The reference solution is given by the lattice code APOLLO. The maximum relative error of k-infinity from NECP-CACTI compared with APOLLO is 0.33%.

0.0000	**APOLLO**
0.0000	**CASMO4**
0.0000	**NECP-CACTI**
0.00%	**Error 1**:Relative error between CASMO4 and APOLLO
0.00%	**Error 2**:Relative error between NECP-CACTI and APOLLO

1.0930	1.0850							
1.1430	1.1110							
1.1530	1.1158							
4.57%	2.40%							
5.49%	2.84%							
1.1060	1.0850	1.0770						
1.1310	1.0990	1.0850						
1.1382	1.1030	1.0886						
2.26%	1.29%	0.74%						
2.91%	1.66%	1.08%						
0.0000	1.0790	1.0760	0.0000					
0.0000	1.1010	1.0860	0.0000					
0.0000	1.1062	1.0891	0.0000					
0.00%	2.04%	0.93%	0.00%					
0.00%	2.52%	1.21%	0.00%					
1.0600	1.0130	0.9600	1.0240	1.0470				
1.0760	1.0240	0.9770	1.0470	1.0550				
1.0783	1.0216	0.9688	1.0493	1.0575				
1.51%	1.09%	1.77%	2.25%	0.76%				
1.73%	0.85%	0.92%	2.47%	1.00%				
1.0530	0.9580	0.3300	0.9750	1.0700	0.0000			
1.0500	0.9690	0.1130	1.0000	1.0650	0.0000			
1.0489	0.9578	0.3124	0.9950	1.0712	0.0000			
-0.28%	1.15%	-65.76%	2.56%	-0.47%	0.00%			
-0.39%	-0.02%	-5.33%	2.05%	0.11%	0.00%			
0.0000	1.0260	0.9770	0.0000	1.0640	0.9640	0.3240		
0.0000	1.0450	0.9970	0.0000	1.0620	0.9780	0.1130		
0.0000	1.0406	0.9870	0.0000	1.0630	0.9729	0.3044		
0.00%	1.85%	2.05%	0.00%	-0.19%	1.45%	-65.12%		
0.00%	1.42%	1.02%	0.00%	-0.09%	0.93%	-6.04%		
1.0750	1.0530	1.0510	1.0670	1.0350	0.9770	0.9190	0.9660	
1.0880	1.0600	1.0490	1.0740	1.0420	0.9890	0.9250	0.9690	
1.0829	1.0490	1.0374	1.0690	1.0320	0.9733	0.9023	0.9474	
1.21%	0.66%	-0.19%	0.66%	0.68%	1.23%	0.65%	0.31%	
0.74%	-0.38%	-1.29%	0.19%	-0.29%	-0.38%	-1.82%	-1.92%	
1.0670	1.0700	1.0660	1.0580	1.0430	1.0240	1.0160	1.0200	1.0450
1.0790	1.0740	1.0690	1.0670	1.0510	1.0290	1.0100	1.0220	1.0490
1.0592	1.0523	1.0482	1.0479	1.0300	1.0048	1.0007	1.0020	1.0225
1.12%	0.37%	0.28%	0.85%	0.77%	0.49%	-0.59%	0.20%	0.38%
-0.73%	-1.65%	-1.67%	-0.96%	-1.24%	-1.88%	-1.51%	-1.76%	-2.15%

Fig. 3 Power distribution of an 1/8 DAYA BAY lattice

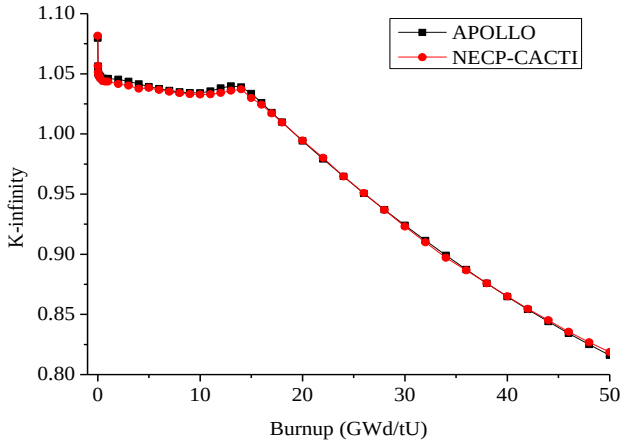


Fig. 4 K-infinity vs burnup for DAYA BAY lattice

LATTICE WITH MOX FUEL

The calculation is not accurate for MOX fuel when multi-group data library adopts 69 energy groups structure.

Because the 69-group structure is not accurate in resonance energy range once Pu-242 shows up. NECP-CACTI adopts 172 energy group structure to for MOX fuel. Following that is the benchmark calculation result of MOX single cell issue published by JAEA, reference solution is given by many famous lattice codes. As shown in Fig. 5, the results of NECP-CACTI locate in the middle of reference solutions.

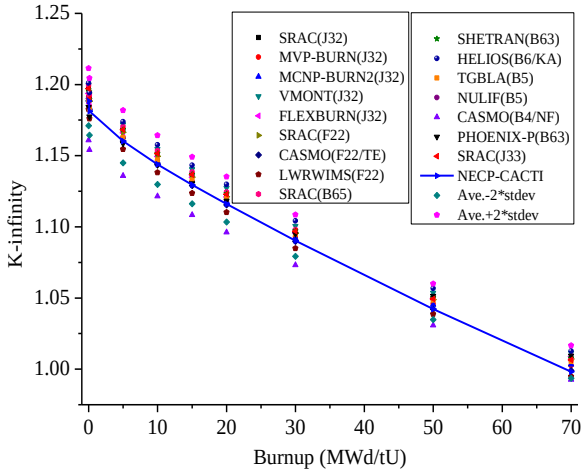


Fig. 5 K-infinity vs burnup for JAEA MOX lattice

CONCLUSIONS

From what has been listed above, lattice code NECP-CACTI has reliable calculation precision in the lattice issues which contain water gap, and acquires the better calculation results in those issues which contain burnable poison and MOX fuel.

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