7ICMSNSE-xxx

JMCT Monte Carlo Simulation Analysis of Full Core PWR Pin-By-Pin and Shielding

Deng Li[1,2*], Li Gang[1,2], Zhang Baoyin[1,2], Shangguan Danhua[1,2], Ma Yan[1,2], Hu Zehua[1,2], Fu Yuanguang[2], Li Rui[2], Hu Xiaoli[2], Cheng Tangpei[2], Shi Dunfu[2]

[1] Institute of Applied Physics and Computational Mathematics (IAPCM),
[2] CAEP Software Center for High Performance Numerical Simulation, Beijing, China
deng_li@iapcm.ac.cn, li_gang@iapcm.ac.cn, zhang_baoying@iapcm.ac.cn, sgdh@iapcm.ac.cn, yan_ma@iapcm.ac.cn, hu_zehua@iapcm.ac.cn, fu_yuanguang@iapcm.ac.cn, li_rui@iapcm.ac.cn, hu_xiaoli@iapcm.ac.cn, chen_tangpei@iapcm.ac.cn, shi_dunfu@iapcm.ac.cn

Abstract

This paper describes the application of the *JMCT* Monte Carlo code to the simulation of Kord Smith Challenge H-M model, BEAVRS model and Chinese SG-III model. For H-M model, the 6.3624 millions tally regions and the 98.3 billion neutron histories do. The detailed pin flux and energy deposition densities obtain. 95% regions have less 1% standard deviation. For BEAVRS model, firstly, we performed the neutron transport calculation of 398 axial planes in the Hot Zero Power (HZP) status. Almost the same results with *MC21* [1] and *OpenMC* [2] results are achieved. The detailed pin-power density distribution and standard deviation are shown. Then, we performed the calculation of ten depletion steps in 30 axial plane cases. The depletion regions exceed 1.5 million and 12,000 processors uses. Finally, the Chinese SG-III laser model is simulated. The neutron and photon flux distributions are given, respectively. The results show that the *JMCT* code well suits for extremely large reactor and shielding simulation.

Key Words: *JMCT*, Monte Carlo, depletion, H-M model, BEAVRS model, SG-III laser model.

1. Introduction

At the M&C2003 conference, Kord Smith Challenge is proposed [3]. At the 2009 American Nuclear Society Mathematics and Computation conference, Hoogenboom and Martin proposed a full-core PWR model (i.e. H-M model) [4]. *MC21* finished the simulation for H-M model in 2010 [5]. At the M&C2013 conference, MIT Computational Reactor Physics Group permits the new Benchmark for Evaluation And Validation and Reactor Simulation (i.e. BEAVRS model) [6]. At the PHYSOR2014 conference, *OpenMC* and *MC21* Monte Carlo code finish the simulation of cycle 1 with depletion and give the power density distribution [7].

The *JPTS* particle transport system is developed by IAPCM. It is based on three support infrastructures *JASMIN*, *JAUMIN* and *JCOGIN*, where *JASMIN* is the adaptive structured mesh infrastructure,

* Corresponding Author: Tel: +86-10-59872183, Fax: +86-10-59872300.
This work was performed under the National High Technology Research and Development Program (863) of China (2012AA01A303) , Nuclear Power Development Project of the State Administration of Science, Technology and Industry for National Defense ([2012]1523) and the National Energy Administration of China (2015ZX06002008).

JAUMIN is the adaptive unstructured mesh infrastructure and *JCOGIN* is the parallel combinatorial geometry infrastructure. In this paper, we mainly introduce *JMCT* Monte Carlo code [8]. The results of H-M, BEAVRS and SG-III models are given, where SG-III model involves the large space, geometry complicated and deep-penetration. For BEAVRS model, we finish the transport calculation in HZP status and obtain the almost same result with *MC21* and *OpenMC*. However, when the depletion being considered, only ten depletion steps are done in 30 axial planes. The part results give in this paper.

2. *JPTS* System and *JMCT* Monte Carlo Code

2.1 *JPTS* system

JPTS is a program system which is developed by IAPCM. It is design for simulation of reactor full core and shielding problems. *JPTS* is developed in the three support infrastructures. The support infrastructure takes the bridge role of the application program and the computer. At present, *JPTS* contains the four codes: *JMCT, JSNT, JBURN, JNuDa* and a suit of data libratory: *NuDa*. Furthermore, the CAD pre-processor *JLAMT* and view pro-processor *TeraVAP* are equipped in the *JPTS* system (see figure 1).

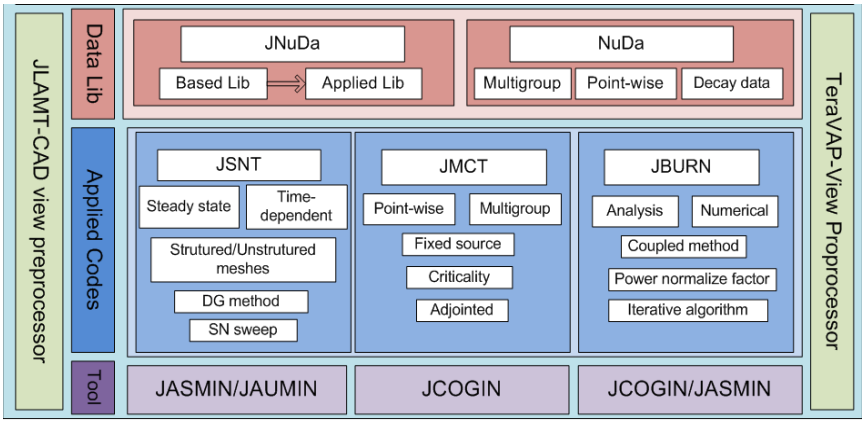


Figure 1 *JPTS* particle transport system

Where: *JSNT*: 3-D discrete ordinates S_N method neutron and photon transport code, which can solve the time-dependent and time-independent (steady state) transport problem with structure and unstructured mesh. *JMCT*: 3-D Monte Carlo neutron and photon transport code, which can solve time-dependent and time-independent transport problem. *JBURN*: the depletion code with analysis (Transmutation Trajectory Analysis (TTA)) and numerical method (Chebyshev Rational Approximation Method (CRAM)). *JBURN* realizes the coupled with *JMCT* and *JSNT*, the depletion region is large enough. *JNuDa*: the cross-section data produce code, which makes the ACE format point-wise cross-section and the ANISN format multigroup cross-section from the base libraries, such as ENDF, CENDL and JENDL etc. *NuDa*: the cross-section libraries, which includes the point-wise library, the multigroup library and the decay library. *JLAMT*: the CAD pre-processor code, which includes the input. *TeraVAP*: the visualization analysis tool for treatment of the simulation results.

2.2 *JMCT* Monte Carlo Code

JMCT (J Monte Carlo Transport) is a general purpose 3-D Monte Carlo neutron, photon or coupled neutron/photon transport code with the combinatorial geometry. It is design for safety evaluation of nuclear systems and performs the comprehensive particle calculation. Also it can be coupled with the depletion for studying the radiation source term/dose/biohazard, material activation and transmutation, etc. The space cell, tally, sample number and memory can be large enough. It is with the capability to simulate the eigenvalues for critical systems and radiation shielding. It is developed on the *JCOGIN* which integrates the geometry operation, the particle track calculation, domain decomposition, random generator and the parallel computation etc. The basic geometry bodies include sphere, cylinder, cone, box and some special body etc. The code is written in C, C++ and FORTRAN 95. It can solve the forward and the adjoint transportation problems. The source type includes the fixed source and the fission source. The modeling is on the CAD interface. The calculated result outputs as picture and the text file. The tally includes the k_{eff}, the flux, energy deposition, power density and reactivity etc.

The key algorithms have the pin-by-pin source produce, tallies, fast critical search of boron concentration, variance reductions, domain decomposition, the coupled parallel computation of MPI (for particles) and OpenMP (for domain), etc. Especially, *JMCT* supports the repeat structure with same geometry and different material.

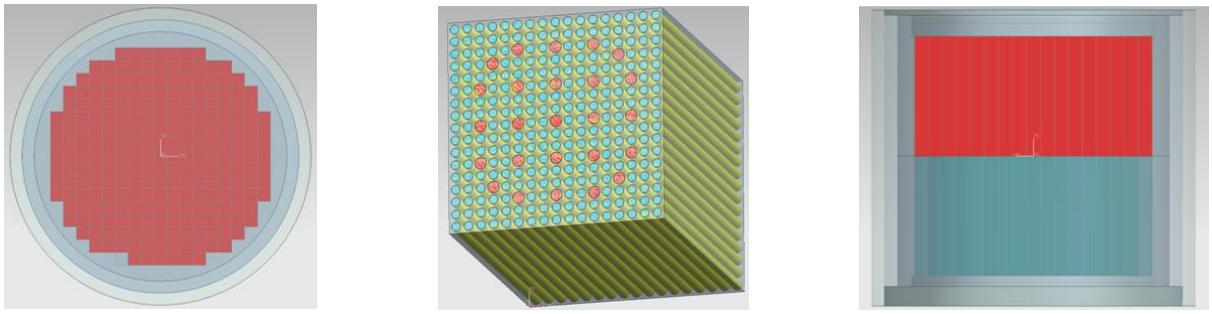
3. Test Models and Simulation Results

3.1 H-M PWR Benchmark Model

We obtain the Hoogenboom-Martin benchmark at the OECD/NEA website at: http://www.oecd-nea.org/dbprog/MonteCarloPerformanceBenchmark.htm. The detailed model data is from the file (http://www.oecd-nea.org/dbprog/documents/MonteCarlobenchmarkguideline_004.pdf). *MC21* obtains the model from OECD/NEA website at http://www.nea.fr/html/dbprog/MonteCarloPerformanceBenchmark.htm.
The core basic parameters as the following:

1) fuel assemblies: 241;
2) axial planes: 100;
3) pins/assembly: 289 (17×17, where 25 guide tube and 264 fuel pins);
4) total tally regions: 6,964,900 (241×17×17×1×100);
5) total regions: 13,929,800 (241×17×17×2×100);
6) Requirement: ≤ 1% standard deviation for 95% fuel pin-powers.

There are approximately 13.95 million regions in this model. For acceptable results, Smith specified the flux standard deviation be less 1% for 95% pins. This standard deviation can ensure that the Monte Carlo result converges after depletion being considered. This model is also called as Kord Smith Challenge. Smith estimated that it would be 2030 before such a calculation could be done in less than one hour on a single CPU. At PHYSOR2010 conference, *MC21* Monte Carlo code given the simulation result [4]. This calculation contained 1000 active cycles and 300 discarded cycles for a total 1300 cycles. Each cycle contained 40 million neutron histories for a total of 52 billion histories. The k_{eff} for this calculation was given. The calculation ran for 1076 minutes (18.0 hours) using 400 processors, and required 6.5 GB of memory per processor.



(a) Arrangement of fuel assemblies (b) Arrangement of pin assembly (c) Axial planes and region

Figure 2 Core cross-section indicating the H-M model by *JMCT*

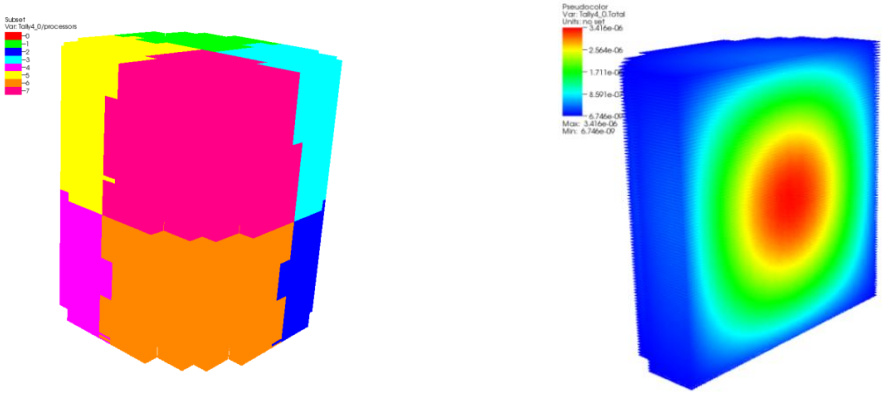
Figure 2 shows the core interface which is plotted by pro-processor *JLAMT* of *JMCT*. The first calculation was made with the run 20000 neutron histories each cycle, skip 50 discard cycles and 130 cycles in total. The statistical result is the last 80 active cycles. Table I shows the comparison of k_{eff} between *MC21* and *JMCT*. The initial source sites were uniformly sampled from a parallelepiped that covers the entire 3-D model. A second calculation was run for the purpose of obtaining the detailed power densities. For this calculation, the tallies included the flux, fission deposition and standard deviations. The tally was for all pin fuel regions (6362400), 81.92 million neutron histories each cycle，600 discard cycles and 1800 cycles in total. The total sample numbers are 98.304 billions. Domain decomposition does 8 parts (2 (x-direction) ×2 (y-direction) ×2 (z-direction)(see Fig.3(a)). The calculations ware run on a Chinese TianHe-II computer with 2048 processors and run time is 25.23 hours. Figure 3 shows the calculation the calculated result. Table II shows the standard deviation distribution and 95% pins satisfy less 1% requirement.

Table I Comparison of k_{eff} between *MC21* and *JMCT*

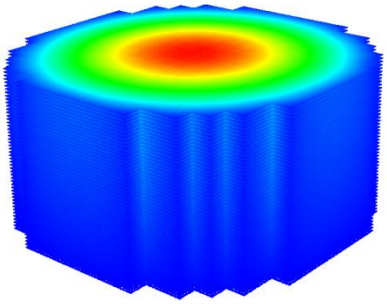
Programs	*MC21*	*JMCT*
k_{eff}	1.005675	1.000822
standard deviation	±0.000724	±0.00023

Table II Max and min standard deviation of flux and energy deposition for all fuel pins

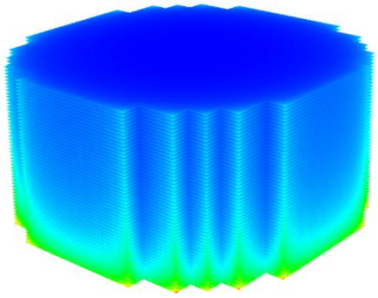
Count	MAX	MIN	95%	99%
Flux	0.02457	0.0012	<0.0063	<0.00961
Energy deposition	0.05523	0.00316	<0.01626	<0.02437



(a) 2×2×2 domain decomposition (b) Pin fluxes



(c) Pin fluxes



(d) Standard deviation of pin fluxes

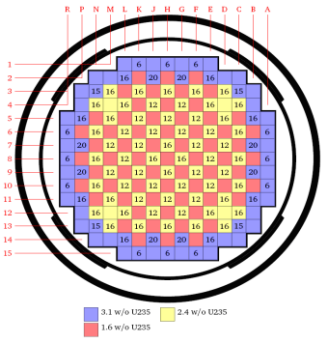
Figure 3 Simulation results of H-M model by *JMCT*

3.2 BEAVRS Model

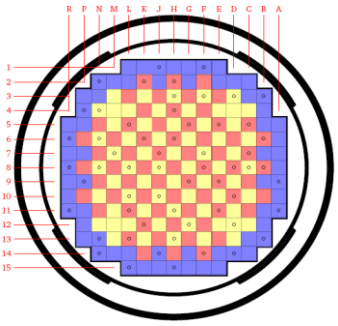
The BEAVRS model was released by MIT Computational Reactor Physics Group in July 7, 2013 (www.crpg.mit.edu)[5]. It includes detailed specification of operating 4-loop Westinghouse PWR with the thermal power of 3411 MW, two cycles of measured data. In the first cycle, it is loaded with 81.8 MT heavy metal. There are 193 fuel assemblies divided into three regions loaded with the enrichment of 1.6 w/o, 2.4 w/o and 3.1 w/o ^{235}U, respectively (see Fig. 4). Each assembly has 17×17 pins bundled by 8 spacers. There are 264 fuel rods, and other 25 pins are guide tubes, burnable absorber rods and instrument tubes. In the axial direction, the active fuel length is 365.76 cm (see Fig. 4(e)). The basic data is as following:

1) fuel assemblies: 193;
2) axial planes: 398;
3) pins/assembly: 289 (17×17, where 25 guide tubes and 264 fuel pins);
4) total tally regions: 22,199,246 (193×17×17×1×398);
5) total regions: 44,398,492 (193×17×17×2×398);
6) Requirement: ≤ 1% standard deviation for 95% fuel pin-powers.

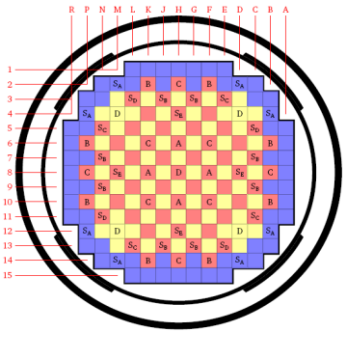
At PHYSOR2014 conference, the results of *MC21* [1] and *OpenMC* [2] were presented [6].



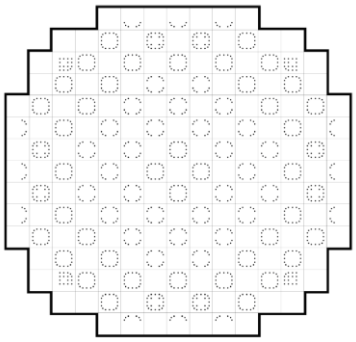
(a) Enrichment zones



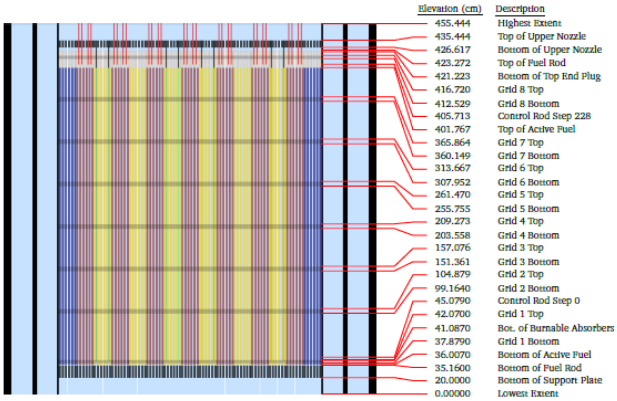
(b) Instrument tube positions



(c) Control rod and shutdown bank positions



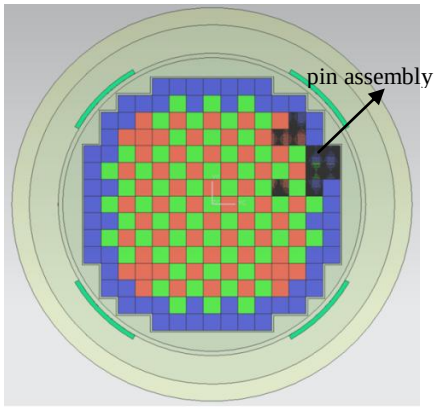
(d) Burnable absorber pins



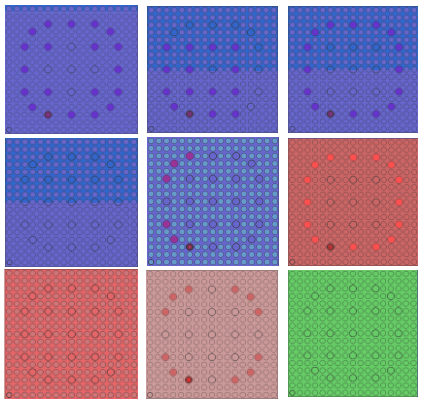
(e) Fuel rod pincell and grid axial specification

Figure 4 Core section of BEAVRS model from reference

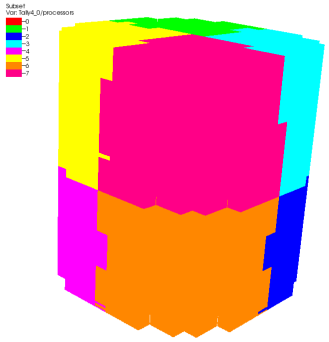
The advanced CAD modeling tool *JLAMT* is applied to build the model. The pins are modeled in details and the spacers are modeled with the suggested configuration (see Fig. 5). In axial direction, 398 UO_2 pellets are in the region with the coordinate from 36.007 cm (bottom of active fuel) to 401.767 cm (top of active fuel). To make sure that the mesh of spacer fully contains the meshes of pellets, the meshes of pellets are not equally divided. *JMCT* finished the modeling according to the report [5]. Figure 5 shows the core radial section and the nine fuel assembly, where the blue assemblies have five types, the red assemblies have three types and the green assemblies have one type.



(a)Core section in radial plane



(b) Nine type assemblies



(c) Domain decomposition (2×2×2)

Figure 5 Core section of BEAVRS model by *JMCT*

(1) Simulation of HZP status

The HZP status is in 398 axial planes. The space domain is decomposed into 8 parts in 2 (x-direction) ×2 (y-direction) ×2 (z-direction)(see Fig.5(c)). The tally was for all pin fuel regions, 4 million neutron histories each cycle，3000 discard cycles and 8000 cycles in total. The total sample numbers are 20 billions. 2000 processors are used and take about 12 hours. Table III shows the k_{eff} comparison of different codes in different status. Table IV shows the reactivity worth of control rods in 556K (560F). Table V shows the standard deviation distribution in 95% confidence level. Figure 6 shows the comparisons of the *MC21* and *JMCT* powers in axial. The maximal Diff is 3.17%, where Diff= (*JMCT*-

MC21)/*JMCT*. Figure 6 shows the comparison of pin power distribution and difference at axial elevation of peak power. Figure 7 shows the axial power shape of the different assembles between *MC21* and *JMCT* as compared to experiment.

Table III keff comparison in different control rod statuses and boron concentration

HZP Critical Boron Evaluation	Boron Concentration	*JMCT* (95% confidence leave)	*OpenMC* (95% confidence leave)	*MC21* (95% confidence leave)
ARO	975	1.000479 ±0.000030	0.99920 ±0.00004	0.9992614 ±0.000004
D in	902	1.002174 ±0.000030	1.00080 ±0.00004	
C,D in	810	1.001419 ±0.000032	1.00023 ±0.00005	
A,B,C,D in	686	0.9999172 ±0.000032	0.99884 ±0.00004	
A,B,C,D,SE,SD,SC in	508	0.9983806 ±0.000032	0.99725 ±0.00004	

Table IV Comparison of reactivity worth of control rod in different statuses and boron concentration

HZP Bank worth	Boron (ppm)	Measure (pcm)	*MC21* (pcm)	*OpenMC* (pcm)	*JMCT* (pcm)
D	938.5	788	773	771±6	770±6
C with D in	856	1203	1260	1234±7	1258±6
B with D,C in	748	1171	1172	1197±7	1162±6
A with D,C,B in	748	548	574	556±6	578±6
SE with D,C,B,A in	597	461	544	501±6	543±6
SD with D,C,B,A,SE in	597	772	786	844±6	781±6
SC with D,C,B,A,SE,SD in	597	1099	1122	1049±6	1107±6

Table V Max and min standard deviation of flux and energy deposition for all fuel pins

Count	MAX	MIN	95%	99%
Flux	0.0091	0.00118	<0.00332	<0.00423
Energy deposition	0.01933	0.00254	<0.0075	<0.00955

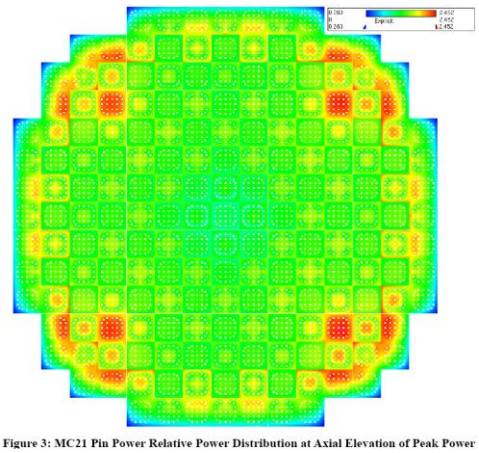
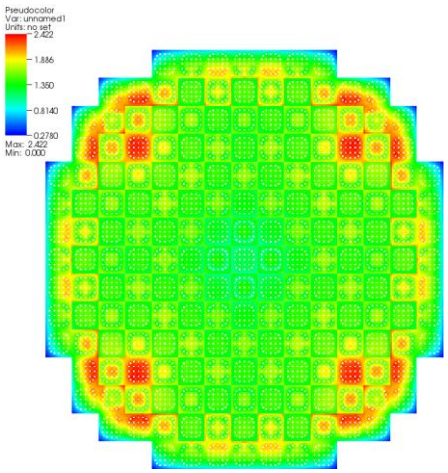


Figure 3: MC21 Pin Power Relative Power Distribution at Axial Elevation of Peak Power

(a)*MC21* result



(b) *JMCT* result

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
	HZP *MC21* results →				0.734	0.891	1.010	0.961	1.023	0.909	0.745		% The Max Diff: 3.173%		
1	*JMCT* results →				0.754	0.917	1.040	0.988	1.046	0.920	0.760		% The Min Diff: 0.000%		
	% Diff (*JMCT* vs *MC21*) →				2.725%	2.918%	2.970%	2.810%	2.248%	1.210%	2.013%				
			0.889	1.209	1.137	0.910	1.105	0.914	1.112	0.923	1.153	1.227	0.900		
2			0.896	1.231	1.168	0.936	1.132	0.943	1.136	0.943	1.179	1.247	0.912		
			0.787%	1.820%	2.726%	2.857%	2.443%	3.173%	2.158%	2.167%	2.255%	1.630%	1.333%		
		0.885	1.196	1.150	0.996	0.991	0.890	0.957	0.898	1.004	1.016	1.172	1.219	0.902	
3		0.897	1.214	1.175	1.021	1.016	0.913	0.980	0.916	1.021	1.032	1.189	1.233	0.909	
		1.356%	1.505%	2.174%	2.510%	2.523%	2.584%	2.403%	2.004%	1.693%	1.575%	1.451%	1.148%	0.776%	
		1.209	1.151	1.392	1.079	0.909	1.011	0.876	1.021	0.924	1.099	1.429	1.183	1.243	
4		1.222	1.170	1.419	1.099	0.928	1.029	0.895	1.034	0.935	1.111	1.439	1.191	1.246	
		1.075%	1.651%	1.940%	1.854%	2.090%	1.780%	2.169%	1.273%	1.190%	1.092%	0.700%	0.676%	0.241%	
	0.742	1.148	1.000	1.086	0.953	1.034	0.889	0.998	0.895	1.051	0.972	1.114	1.032	1.194	0.768
5	0.748	1.159	1.016	1.095	0.963	1.046	0.895	1.005	0.898	1.054	0.974	1.112	1.031	1.179	0.761
	0.809%	0.958%	1.600%	0.829%	1.049%	1.161%	0.675%	0.701%	0.335%	0.285%	0.206%	-0.180%	-0.097%	-1.256%	-0.911%
	0.905	0.926	1.004	0.917	1.039	0.886	0.974	0.836	0.982	0.905	1.061	0.942	1.031	0.952	0.927
6	0.904	0.928	1.006	0.923	1.043	0.891	0.972	0.836	0.975	0.897	1.054	0.935	1.025	0.943	0.923
	-0.110%	0.216%	0.199%	0.654%	0.385%	0.564%	-0.205%	0.000%	-0.713%	-0.884%	-0.660%	-0.743%	-0.582%	-0.945%	-0.431%
	1.040	1.128	0.911	1.020	0.891	0.971	0.800	0.841	0.807	0.983	0.905	1.049	0.921	1.152	1.058
7	1.029	1.118	0.903	1.019	0.891	0.969	0.797	0.834	0.801	0.973	0.899	1.034	0.916	1.137	1.046
	-1.058%	-0.887%	-0.878%	-0.098%	0.000%	-0.206%	-0.375%	-0.832%	-0.743%	-1.017%	-0.663%	-1.430%	-0.543%	-1.302%	-1.134%
	0.985	0.944	0.981	0.896	1.000	0.835	0.834	0.738	0.843	0.843	1.022	0.909	0.998	0.952	1.001
8	0.970	0.931	0.968	0.887	0.994	0.833	0.830	0.734	0.834	0.836	1.006	0.896	0.982	0.943	0.987
	-1.523%	-1.377%	-1.325%	-1.004%	-0.600%	-0.240%	-0.480%	-0.542%	-1.068%	-0.830%	-1.566%	-1.430%	-1.603%	-0.945%	-1.399%
	1.049	1.145	0.920	1.032	0.900	0.974	0.800	0.837	0.801	0.988	0.911	1.050	0.933	1.157	1.062
9	1.030	1.116	0.903	1.021	0.890	0.967	0.796	0.831	0.797	0.973	0.896	1.031	0.914	1.132	1.040
	-1.811%	-2.533%	-1.848%	-1.066%	-1.111%	-0.719%	-0.500%	-0.717%	-0.499%	-1.518%	-1.647%	-1.810%	-2.036%	-2.161%	-2.072%
	0.916	0.939	1.021	0.931	1.049	0.894	0.975	0.838	0.979	0.906	1.068	0.948	1.044	0.960	0.938
10	0.908	0.929	1.009	0.923	1.039	0.889	0.965	0.833	0.969	0.893	1.047	0.928	1.017	0.938	0.916
	-0.873%	-1.065%	-1.175%	-0.859%	-0.953%	-0.559%	-1.026%	-0.597%	-1.021%	-1.435%	-1.966%	-2.110%	-2.586%	-2.292%	-2.345%
	0.750	1.165	1.022	1.103	0.961	1.044	0.895	1.001	0.900	1.060	0.986	1.124	1.044	1.194	0.767
11	0.747	1.161	1.017	1.096	0.962	1.042	0.891	0.996	0.892	1.044	0.965	1.101	1.023	1.169	0.754
	-0.400%	-0.343%	-0.489%	-0.635%	0.104%	-0.192%	-0.447%	-0.500%	-0.889%	-1.509%	-2.130%	-2.046%	-2.011%	-2.094%	-1.695%
		1.223	1.171	1.415	1.096	0.919	1.022	0.892	1.026	0.936	1.110	1.442	1.198	1.260	
12		1.227	1.174	1.420	1.097	0.923	1.023	0.888	1.021	0.925	1.099	1.422	1.179	1.234	
		0.327%	0.256%	0.353%	0.091%	0.435%	0.098%	-0.448%	-0.487%	-1.175%	-0.991%	-1.387%	-1.586%	-2.063%	
		0.892	1.203	1.168	1.005	0.999	0.891	0.967	0.909	1.015	1.026	1.195	1.239	0.917	
13		0.898	1.212	1.174	1.016	1.010	0.906	0.971	0.906	1.012	1.020	1.177	1.220	0.900	
		0.673%	0.748%	0.514%	1.095%	1.101%	1.684%	0.414%	-0.330%	-0.296%	-0.585%	-1.506%	-1.533%	-1.854%	
			0.888	1.218	1.148	0.912	1.108	0.928	1.126	0.934	1.172	1.241	0.918		
14			0.896	1.228	1.161	0.930	1.119	0.934	1.124	0.932	1.165	1.228	0.901		
			0.901%	0.821%	1.132%	1.974%	0.993%	0.647%	-0.178%	-0.214%	-0.597%	-1.048%	-1.852%		
					0.737	0.895	1.017	0.970	1.031	0.914	0.754				
15					0.747	0.909	1.032	0.974	1.035	0.912	0.752				
					1.357%	1.564%	1.475%	0.412%	0.388%	-0.219%	-0.265%				

Figure 6 Comparison of power and difference at axial elevation of peak power between *JMCT* and *MC21*

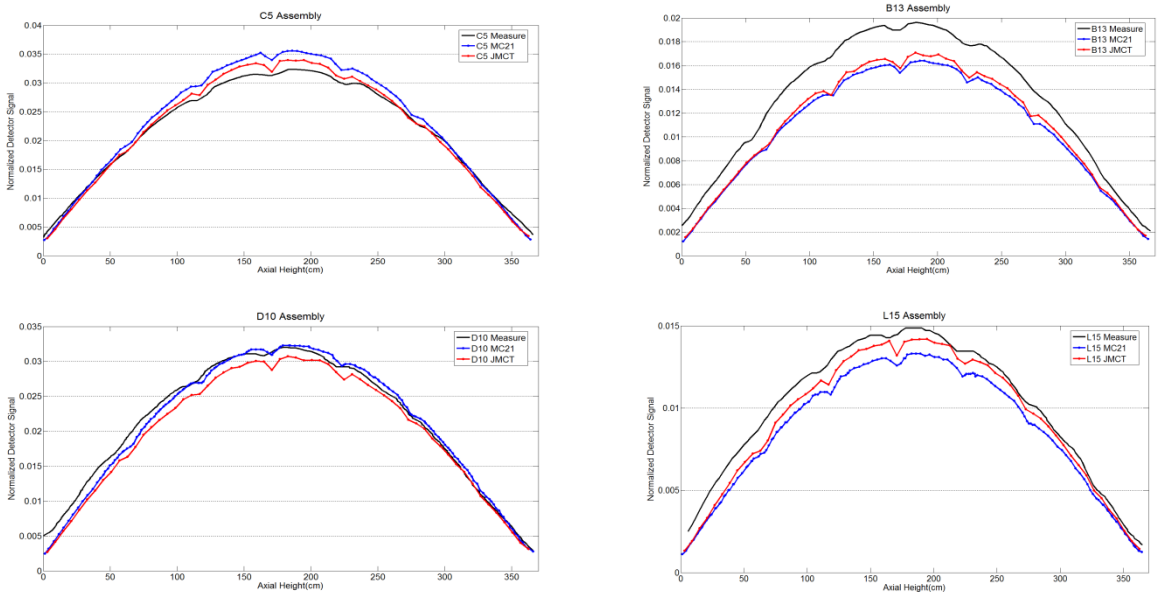


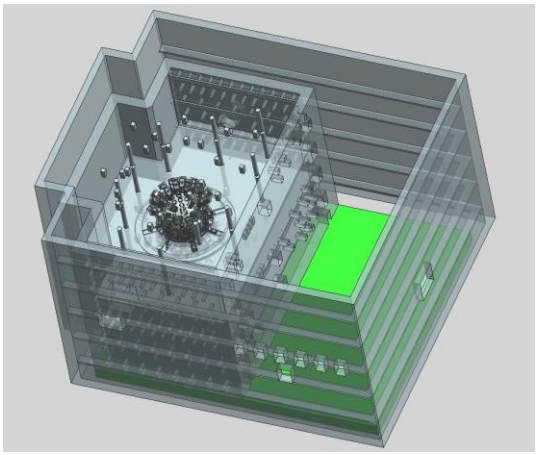
Figure 7 The axial power shape between *MC21* and *JMCT* as compared to experiment

(2) Depletion being considered

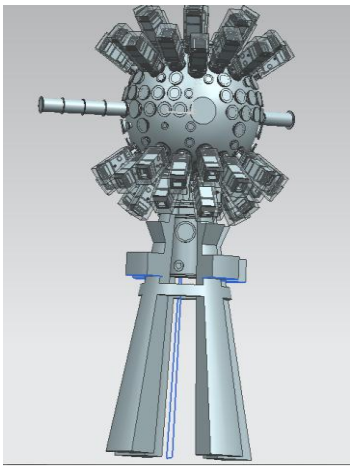
The coupled neutron transport and depletion is run in 30 axial planes, where the depletion region is up to 1528560 (193×264×1×30). The space domain is decomposed into 8 parts. Due to the model too large, ten depletion steps are calculated. It takes about 1 hour with 12000 processors on Chinese TianHe-II computer. Due to the *JMCT* not coupled with thermal hydraulics, the temperature doesn't change. So the result isn't precise enough. But it shows that *JMCT* is with capability of simulation for the model exceeding million depletion regions.

3.3 Chinese SG-III Laser Model

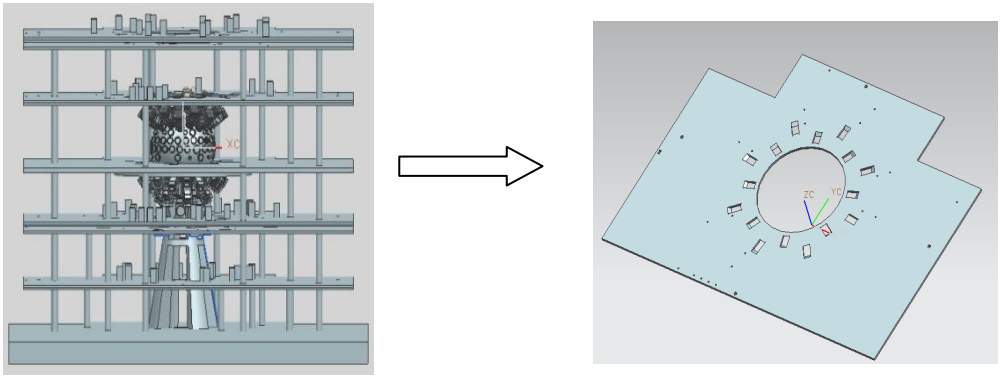
Chinese SG-III laser device is large as big as a football. It is applied to drive the nuclear fusion reaction by laser. Figure 8 shows the modeling which is done by *JMCT* pro-processor. The tally does for all floors. Figure 9 gives the neutron and photon flux distributions in the base of the fourth floor. Mesh tally does and it has about 0.63 million meshes. The 0.4 billion neutron histories are simulated by 720 processors. The 3.1 CPU hours are taken. Figure 10 shows the calculation results, where the source is a 14.1 MeV Deuterium-Tritium neutron point source.



(a)Building

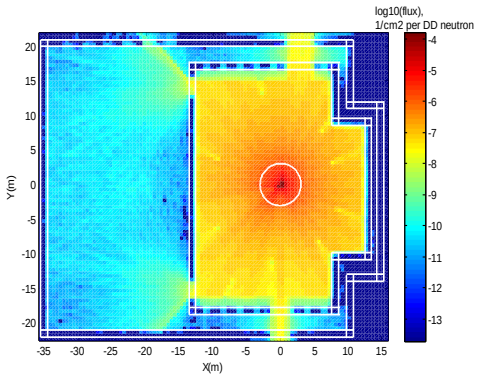


(b) Target room

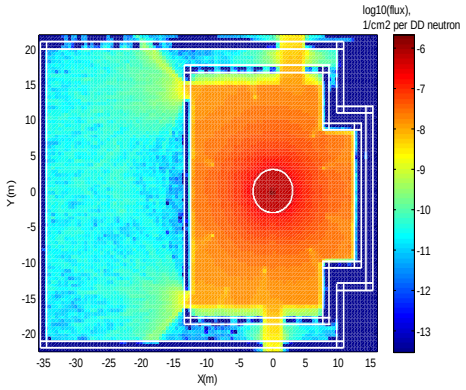


(c) Tally surface and location

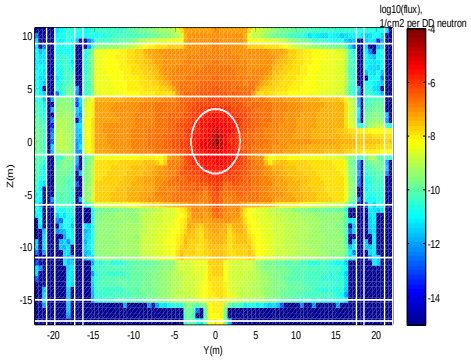
Figure 8 Section of Chinese SG-III laser device



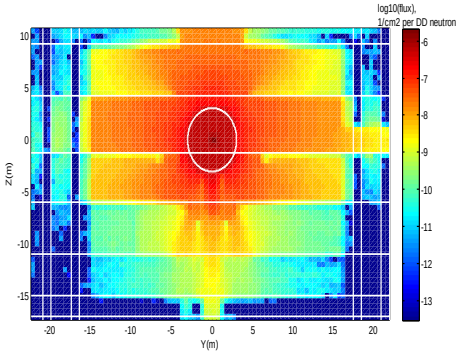
(a) Neutron flux in horizontal plane



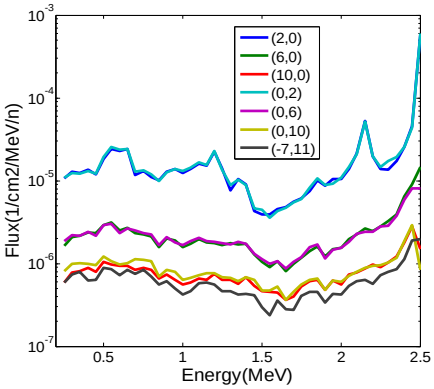
(b) Photon flux in horizontal plane



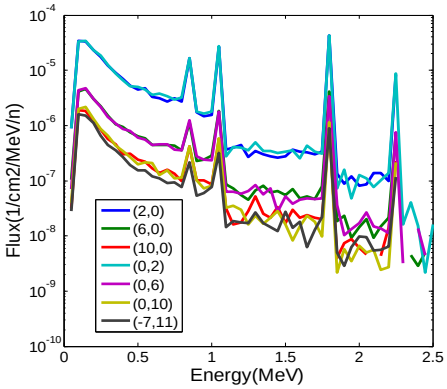
(c) Neutron flux in vertical plane



(d) Photon flux in vertical plane



(e) Neutron energy spectrum in each floor



(f) Photon energy spectrum in each floor

Figure 9 Flux and energy spectrums of each floor in D-T reaction

4. Conclusion

JMCT is with the capability of the full-core pin-by-pin simulation. The H-M model and HZP status of the changeling benchmark BEVAUS are calculated. The results agree very well with the experimental data and the simulation results by *MC21* and *OpenMC*. The complicated SG-III model shows the

strong modeling and simulation capability of *JMCT*. The transport with depletion is developed as well. The calculated results will be presented in future. It well suits to simulate the large reactor analysis and shielding problem. The depletion complicates uncertainty quantification and propagation of error will be considered in our next work. Furthermore, it needs to find some new measures to reduce the computational fee. At present, some challenges still exist in simulation of the BEAVRS model. It needs to develop new algorithms.

5. References

[1] D. P. Griesheimer, et al., "MC21 v.6.0 - A Continuous-Energy Monte Carlo Transport Code with Integrated Reactor Feedback Capabilities," Ann. Nucl. Energy, in press (2015).

[2] P.K. Romano, et al., "OpenMC: A state-of-the-art Monte Carlo code for research and development," Ann. Nucl. Energy, in press (2015).

[3] Kord Smith, "Reactor Core Methods," invited lecture at M&C 2003, April 6–10, Gatlinburg, TN, USA (2003).

[4] J. Eduard Hoogenboom and William R. Martin, "A Proposal for a Benchmark to Monitor the Performance of Detailed Monte Carlo Calculation of Power Densities in a Full Size Reactor Core", Proc. 2009 Int. Conf. on Math., Comp. Meth., & Reactor Phys., American Nuclear Society, May 3–7, 2009, Saratoga Springs, NY, USA, on CD-ROM (2009).

[5] Daniel J. Kelly, Thomas M. Sutton, Timothy H. Trumbull, and Peter S. Dobreff, "MC21 Monte Carlo Analysis of the Hoogenboom-Martin Full-Core PWR Benchmark Problem", PHYSOR 2010 – Advances in Reactor Physics to Power the Nuclear Renaissance, Pittsburgh, Pennsylvania, USA, May 9-14, 2010, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2010).

[6] "MIT Benchmark for Evaluation And Validation of Reactor Simulations," RELEASE rev. 1.0.1, MIT Computational Reactor Physics Group, July 7, 2013.

[7] Daniel J. Kelly, Bryan R. Herman, et al., "Analysis of Select BEAVRS PWR Benchmark Cycle 1 Results Using MC21 and OpenMC", PHYSOR 2014 – The Role of Reactor Physics Toward a Sustainable Future, Kyoto, Japan, September 28 – October 3, 2014.

[8] Li Deng, Tao Ye, Gang Li et al., "3-D Monte Carlo Neutron-Photon Transport Code JMCT and Its Algorithms", PHYSOR 2014, Kyoto, Japan, September 28 – October 3, 2014.