VERA Solution of Zero Power Physics Tests (ZPPT) Using DeCART2D - MASTER

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Abstract – *Accurate and reliable computer codes for neutronics are essential for nuclear reactor design and operation since they permit the simulation of neutron behavior inside the reactor core. These simulations are critical for anticipating the reactor's performance, safety, and efficiency. In order to ensure the safe operation of nuclear reactors and the advancement of new reactor technologies, the accuracy and reliability of these codes are of the utmost importance. The modeling and simulation codes' accuracy and reliability are tested using the Virtual Environment for Reactor Analysis VERA Core Physics Benchmark's problems. MASTER's neutronics model solves the space-time dependent neutron diffusion equations with the advanced nodal methods and DeCART2D a Deterministic Core Analysis based on Ray Tracing, have been developed in Korea Atomic Energy Research Institute (KAERI) to design and analyze the Pressurized Water Reactor (PWR). This study aims to validate the DeCART2D - MASTER code system for the successful completion of the calculations related to the Zero Power Physics Tests (ZPPT) of VERA pressurized water reactor that are carried out at the start of each fuel cycle startup. Several critical configuration estimates, and RCCA bank reactivity worths are among them. The calculation results are compared to ZPPT OF VERA benchmark*

Keywords: *VERA Benchmark, DeCART2D and MASTER codes, Zero Power Physics Tests*

I. Introduction

VERA Core Physics Benchmark Progression Problems [1] are developed to assist nuclear software and methods programmers and analysts, since the reference solution is measured on a real life rector core, the software that solves such problems shall be verified and validated. This paper has solved problem five, which provides measured data for the initial startup of WBN1 for reactor methods benchmarking purposes, using the codes DeCART2D and MASTER.

DeCART2D and MASTER are codes used for neutrons transport calculations to design and model nuclear reactor core. The codes use two-step procedure based system. DeCART2 is a 2D deterministic neutron transport code, its main purpose is to generate assembly-wise and reflectors homogenized condensed group constants (HGC) [2] to be used in MASTER. Which is a nodal diffusion core analysis code for Pressurized Water Reactor core design equipping various calculation capabilities, to analyze and study the performance of a reactor core in 3D geometry based on two-group diffusion theory [3]. The process starts by generating HGC files for each fuel assembly and each reflector using DeCART2D, then a utility codes named PROLOG and PROMARX used to convert the HGC files to cross section library format for MASTER.

II. Physical Reactor ZPPT Problem Description

The problem at hand consists of a full core of fuel assemblies of the Westinghouse 17x17 fuel assembly type according to the of Watts Bar Nuclear Unit 1 (WBN1) Cycle1 initial loading pattern at beginning-of-life (BOL) and Hot Zero Power (HZP) isothermal conditions. and all the specification are given by the CASL VERA Core Physics Benchmark Progression Problem Specifications revision 4 [1].

In this problem the reactor core is presumed to be critical for the first 10 cases. The regulatory Bank D, was positioned at 167 steps and a boron concentration of 1285 ppm to reach the core initial criticality. In addition to initial criticality all rods out (ARO) position and other 8 configurations were modeled for each control rods position during critical position test as shown in Table I. Cases 11 to 30 were also modeled as specified in VERA benchmark.

Table I ZPPT problem VERA benchmark cases [1]

Case	Description	Boron (ppm)	Temp (K)	A	B	C	D	SA	SB	SC	SD	
1	Initial	1285	565	-	-	-	167	-	-	-	-	Criticals
2	ARO	1291	↓	-	-	-	-	-	-	-	-	
3	Bank A	1170	↓	0	-	-	97	-	-	-	-	
4	Bank B	↓	↓	-	0	-	113	-	-	-	-	
5	Bank C	↓	↓	-	-	0	119	-	-	-	-	
6	Bank D	↓	↓	-	-	-	18	-	-	-	-	
7	Bank SA	↓	↓	-	-	-	69	0	-	-	-	
8	Bank SB	↓	↓	-	-	-	134	-	0	-	-	
9	Bank SC	↓	↓	-	-	-	71	-	-	0	-	
10	Bank SD	↓	↓	-	-	-	71	-	-	-	0	
11	ARO	↓	↓	-	-	-	-	-	-	-	-	Rod Worths
12	Bank A	↓	↓	0	-	-	-	-	-	-	-	
13	Bank B	↓	↓	-	0	-	-	-	-	-	-	
14	Bank C	↓	↓	-	-	0	-	-	-	-	-	
15	Bank D	↓	↓	-	-	-	0	-	-	-	-	
16	Bank SA	↓	↓	-	-	-	-	0	-	-	-	
17	Bank SB	↓	↓	-	-	-	-	-	0	-	-	
18	Bank SC	↓	↓	-	-	-	-	-	-	0	-	
19	Bank SD	↓	↓	-	-	-	-	-	-	-	0	
20	D @ 0%	1230	565	-	-	-	0	-	-	-	-	Bank D Integral Worth Curve
21	D @ 10%	↓	↓	-	-	-	23	-	-	-	-	
22	D @ 20%	↓	↓	-	-	-	46	-	-	-	-	
23	D @ 30%	↓	↓	-	-	-	69	-	-	-	-	
24	D @ 40%	↓	↓	-	-	-	92	-	-	-	-	
25	D @ 50%	↓	↓	-	-	-	115	-	-	-	-	
26	D @ 60%	↓	↓	-	-	-	138	-	-	-	-	
27	D @ 70%	↓	↓	-	-	-	161	-	-	-	-	
28	D @ 80%	↓	↓	-	-	-	184	-	-	-	-	
29	D @ 90%	↓	↓	-	-	-	207	-	-	-	-	
30	D @ 100%	↓	↓	-	-	-	-	-	-	-	-	

II.A. Single-Assembly Description

The assembly has a consistent fuel enrichment and is a typical 17x17 Westinghouse fuel configuration. The assembly consists of 264 fuel rods, one instrument tube in the middle, and 24 guide tubes providing structure and position for AIC-B4C rod cluster control assembly (RCCA) or Pyrex burnable poison rods. Table II lists all the basic geometric requirements for the materials for the fuel rods and guide tubes. Fig. 1 and Table III provide the assembly's geometrical requirements.

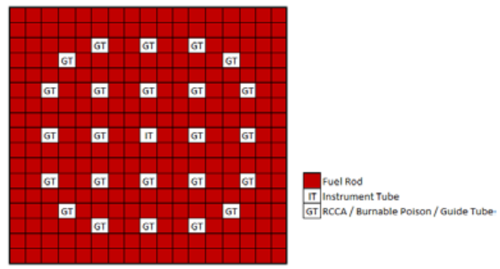

Fig. 1. Assembly Layout Showing Guide Tubes (GT) and Instrument Tube (IT) placement

Table II Fuel Rod and Guide Tube Descriptions [1]

Input	Value
Fuel Enrichment – zone 1	2.11%
Fuel Enrichment – zone 2	2.619%
Fuel Enrichment – zone 3	3.1%
Fuel Density	10.257 g/cc
Pellet Radius	0.4096 cm
Inner Clad Radius	0.418 cm
Outer Clad Radius	0.475 cm
Inner Guide Tube Radius	0.561 cm
Outer Guide Tube Radius	0.602 cm
Inner Instrument Tube Radius	0.559 cm
Outer Instrument Tube Radius	0.605 cm
Clad / Guide Tube Materials	Zircaloy-4
Rod Height	385.1 cm
Plenum Height	16.0 cm
Fuel Stack Height	365.76 cm
End Plug Heights (x2)	1.67 cm

Table III Assembly Description [1]

Input	Value
Rod Pitch	1.26 cm
Assembly Pitch	21.50 cm
Inter-Assembly Half Gap	0.04 cm
Total Assembly Height	406.337 cm
Bottom Nozzle Height	6.053 cm
Top Nozzle Height	8.827 cm

II.B. Full-Core Description

The full-core loading pattern in quarter symmetry for WBN1 as described in CASL are shown in Fig. 2, zone 1 has a 2.11% enrichment, zone 2 has a 2.619% enrichment, and zone 3 has a 3.10% enrichment. The figure also present detailed core layout guidelines for control banks bank IDs A to D represent the regulatory control banks, while SA to SD represent the shutdown banks. Table IV displays the reactor operating conditions for this problem.

Table IV reactor operating conditions [1]

Input	Value
Power	0% FP
Inlet Coolant Temperature	565 K
Inlet Coolant Density	0.743 g/cc
Reactor Pressure	2250 psia
Initial Boron Concentration	1285 ppm
Initial Critical Bank D Position	167 steps

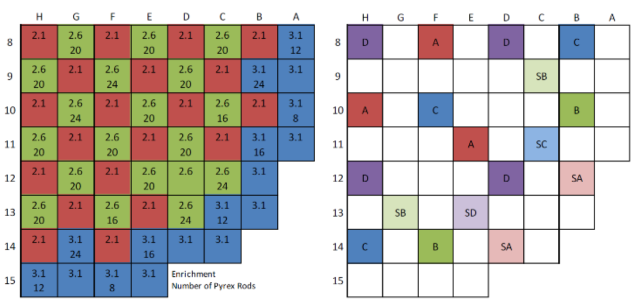

Fig. 2. Core and control banks Layout for Watts Bar Unit 1 Cycle 1

III. Methodology

In this study DeCART2D (Deterministic Core Analysis based on Ray Tracing) code is used to generates assembly-wise homogenized group constant (HGC) for fuel assemblies and the reflectors axial and radial. Based on the decryption provided in section 2.1 and 2.2, 10 fuel assembles were model to generate the fuel assembles HGC files. Fig. 3 shows an example of 1/8 rotational fuel assembly [2].

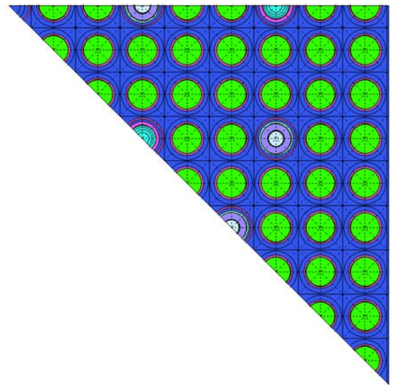

Fig. 3. Radial configuration of fuel assembly

For axial reflector DeCART2D is used first to generate HGC file for bottom and top axial reflector nodes from 1 D core model rather than the two-node approach for accurate modeling [4]. Then PROMARX is used to generate effective axial reflector XS data by reading the HGC files. Fig. 4 depicts the model of a simplified 1-D axial reflector.

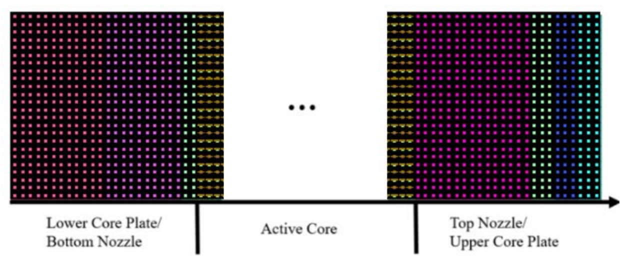

Fig. 4. Simplified 1-D axial reflector

For radial reflector, the reactor baffle plates, barrel, neutron pad, and moderator are modeled using 2-D core model in DeCART2D to generate HGC files as shown in Fig. 5.

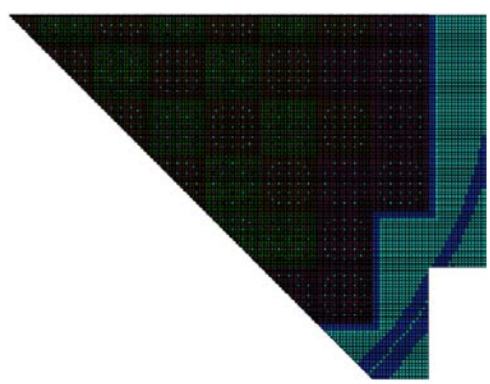

Fig. 5. Radial reflector model of VERA benchmark

To convert HGC files for the fuel assemblies, axial and radial reflectors to MASTER cross section library format, the PROLOG [5] and PROMARX [4] codes are employed as depicted in Fig. 6.

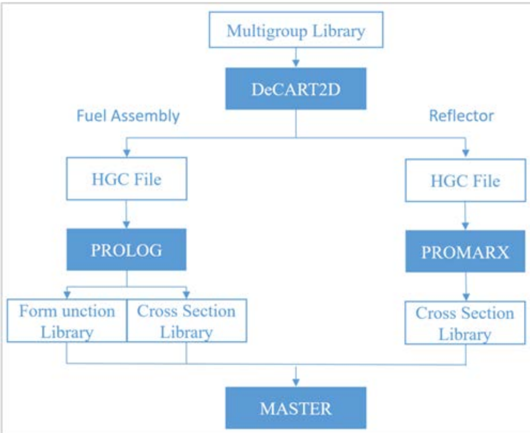

Fig. 6. DeCART-MASTER codes system

The MASTER input model utilizing the cross section library generated by DeCART2D is created using the core loading pattern, control rod map, axial core configuration, and reactor operating conditions in Table IV, to perform zero power physics test (ZPPT) calculations as described in VERA benchmark [MASTER]. (ZPPT) calculations as shown in Table I includes estimates of core critical configurations, the RCCA bank reactivity worth, and radial and axial assembly power distribution.

The eigenvalue (k_{eff}) difference is obtained as in Eq. (1), and the relative difference specified in Eq. (2) is used to compare the power profiles and control rod worth.

$$\mathrm{k_{eff}\ difference\ [pcm]} = \left(\mathrm{k_{eff,S}} - \mathrm{k_{eff,R}}\right) \times 10^5 \quad (1)$$

$$\mathrm{Relative\ \ difference\ [\%]} = \frac{\mathrm{S-R}}{\mathrm{R}} \times 100 \quad (2)$$

where S is the DeCART2D-MASTER solution, R is the reference solution, including measured data and calculated by CE KENO-VI [1].

IV. Results

Table V shows the eigenvalues estimated by CE KENO-VI as the reference and MASTER [1], as well as the reactivity differences between MASTER and CE KENO-VI.

Table V CE KENO-VI eigenvalue reference results and MASTER solution with the difference

Case	k-effective		Difference [pcm]	Relative difference [%]
	CE KENO-VI [1]	MASTER		
1	0.999899	0.999132	-76.7	0.076708
2	1.000321	0.999283	-103.8	0.103767
3	0.998797	0.998757	-4	0.004005
4	0.999358	0.99892	-43.8	0.043828
5	0.999039	0.99892	-11.9	0.011911
6	0.999084	0.998339	-74.5	0.074568
7	0.999022	0.998881	-14.1	0.014114
8	0.999324	0.998923	-40.1	0.040127
9	0.998983	0.998949	-3.4	0.003403
10	0.998976	0.998951	-2.5	0.002503
11	1.012841	1.011711	-113	0.111567
12	1.003716	1.002934	-78.2	0.077910
13	1.003941	1.00274	-120.1	0.119629
14	1.002843	1.002048	-79.5	0.079275
15	0.998815	0.997913	-90.2	0.090307
16	1.008281	1.007008	-127.3	0.126254
17	1.002018	1.001068	-95	0.094809
18	1.007749	1.006591	-115.8	0.114910
19	1.007745	1.006591	-115.4	0.114513
20	0.992755	0.991891	-86.4	0.087031
21	0.993162	0.992528	-63.4	0.063837
22	0.994555	0.994434	-12.1	0.012166
23	0.997369	0.997404	3.5	0.003509
24	1.000279	1.000101	-17.8	0.017795
25	1.002542	1.002115	-42.7	0.042592
26	1.004163	1.003545	-61.8	0.061544
27	1.005300	1.004538	-76.2	0.075798
28	1.006073	1.005168	-90.5	0.089954
29	1.006468	1.005464	-100.4	0.099755
30	1.006584	1.005503	-108.1	0.107393

Table VI displays the initial criticality and RCCA banks worth for the measured data, CE KENO-VI derived reference, MASTER solution, and the differences between them. Bank A has a maximum difference of 3.7% with CE KENO-VI and 6.1% with Measured.

Table VI Measured, CE KENO-VI and MASTER RCCA bank worth results

Test Result	Measured [1]	CE KENO-VI [1]	MASTER	Relative difference with Measured	Relative difference with CE KENO-VI
Initial Criticality	1	0.999899	0.999132	-86.875407	-76.774387
Bank A Worth (pcm)	843	898	865	2.61%	-4%
Bank B Worth	879	875	884	0.60%	1%
Bank C Worth	951	984	953	0.23%	-3%
Bank D Worth	1342	1386	1367	1.84%	-1%
Bank SA Worth	435	447	462	6.12%	3%
Bank SB Worth	1056	1066	1051	-0.49%	-1%
Bank SC Worth	480	499	503	4.74%	1%
Bank SD Worth	480	499	503	4.74%	1%
Total Bank Worths	6467	6654	6587	1.86%	-1%

The Bank D differential and integral worth were calculated with 10% insertion increments and compared to CE KENO-VI, Figs. 7 and 8. depicts these values and their difference with CE KENO-VI reference.

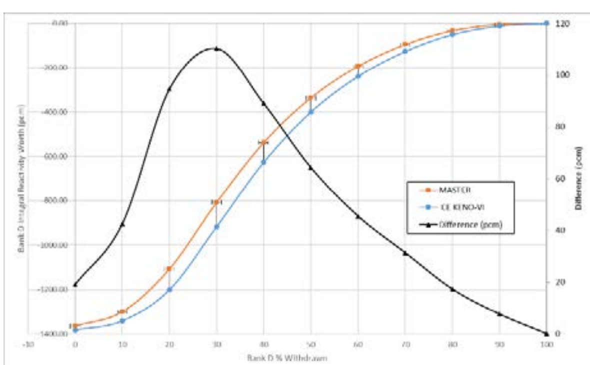

Fig. 7 Bank D Integral Worth Curve

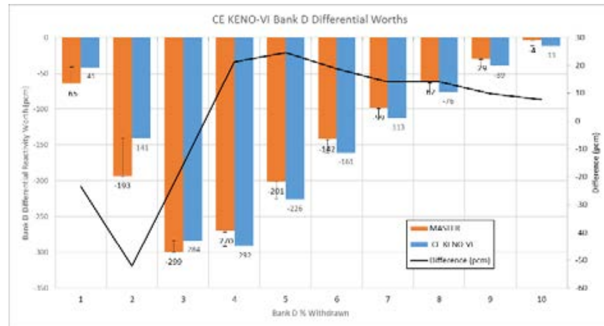

Fig. 8. Bank D Differential Worth

In contrast to the previous cases, an additional case was modeled that did not include the in-core instrument thimbles in order to maintain octant symmetry and provide lower power distribution uncertainty. The comparison of the radial and axial power distributions for the initial critical condition as derived by CE KENO-VI reference and MASTER are shown in Figs. 9 and 10. The highest differences in radial power distribution is 3.56% and the highest axial power distribution is 17.24% at 285.90 cm elevation.

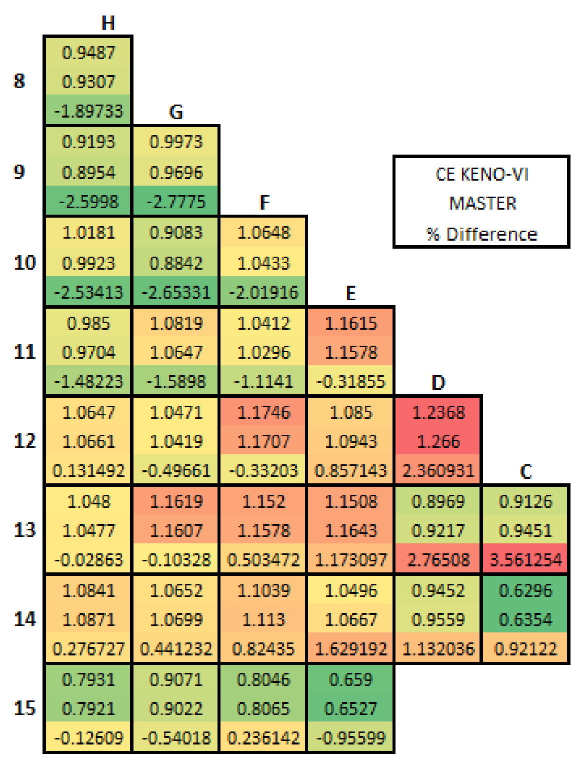

Fig. 9 Radial power distribution and the difference between CE KENO-VI and MASTER

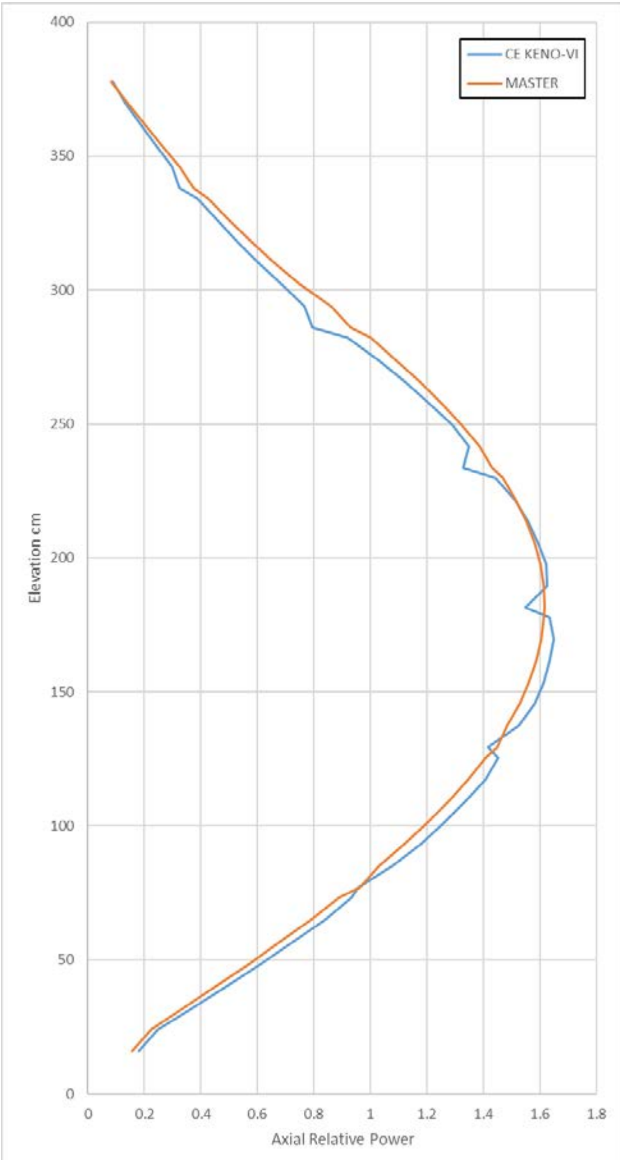

Fig. 10 CE KENO-VI and MASTER Average Axial Power Distribution

V. Conclusions

The DeCART2D-MASTER nuclear design codes are used to perform zero power physics test calculations based on VERA benchmark core at hot zero power isothermal condition. The DeCART2D code was used to generate three different types of HGC files. Then, these HGC were converted using PROLOG and PROMARX to cross section library format to be used in MASTER code. Zero power physics test (ZPPT) calculations are performed using MASTER code generating multiple nuclear parameters including estimates of core critical configurations, the RCCA bank reactivity worth, and radial and axial power distribution. Results are compared with CE KENO-VI reference solutions and WBN1 measured data [1]. Compared to measured data and the reference solution the majority of the parameters' uncertainty is acceptable. The capability of DeCART2D-MASTER for nuclear designs can thus be said to be adequate.

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References

1. Andrew T. Godfrey, “VERA Core Physics Benchmark Progression Problem Specification,” CASL-U-2012-0131-004, Rev. 04, Aug. 29, 2014.
2. J. Y. Cho, et al., “DeCART2D v1.1 User’s Manual,” KAERI/UM-40/2016, 2016.
3. J. Y. Cho, et al., “MASTER v4.0 User’s Manual,” KAERI/UM-41/2016, 2016.
4. C. B. Shim, et al., “Improvement of Axial Reflector Cross Section Generation Model for PWR Core Analysis,” Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, October 27-28, 2016.
5. J. S. Song, et al., “PROLOG1.1 User’s Manual,” KAERI/UM-4/99, 1999.