TVA Watts Bar Unit 1 Cycle 1 Multi-physics Depletion Analysis with STREAM3D

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1. Introduction

With the attraction of direct whole core calculation and the rapid growth in computer technologies, a direct new transport code, STREAM3D [1] (Steady-state and transient reactor analysis with method of characteristics), has been developed in 2013 at Ulsan National Institute Science and Technology laboratories. Unlike conventional 3D MOC codes using the 2D/1D method, 3D/MOC [2] (diamond-difference method) has been adopted into STREAM3D. STREAM3D can perform multi-physics and multicycle simulations as well as standalone simulations. Verification and validation are crucial parts to evaluate code system performance. Therefore, the Consortium for Advanced Simulation of LWRs (CASL) offers a Virtual Environment for Reactor Applications (VERA) Multi-Physics Core Benchmark [3]. VERA address very detailed reactor core structure specification and include a series of the problem of Tennessee Valley Authority (TVA) Watts Bar Unit 1 Cycle 1 (WB1C1) initial core startup exercises and results, including 2D and 3D fuel assembly exercises. Organization for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) extended the VERA benchmark publication. This new publication includes 7 exercises comprising Watts Bar Unit 1 Cycle 1-2-3.[4] STREAM3D results will be simulated for Cycle 1 based on OECD publication and will be compared with benchmark results in CASL, composed of plant data and high-fidelity Monte Carlo code KENO-VI.

2. Methods and Results

This section will give TVA Watts Bar I Cycle 1 reactor core model and data. Reactor core modeling information and simulation features in STREAM3D will be shared. The Benchmark problem set is divided into three exercises for Cycle 1, which are a stand-alone zero power start-up physics test (ZPTT) at Hot Zero Power (HZP), Hot Full Power (HFP) Critical Boron Concentration (CBC) as well as radial assembly power distribution and coolant exit temperature, and boron letdown curve during cycle 1 depletion, respectively.

2.1 TVA Watts Bar Unit 1

The Watts Bar Unit 1 is a Westinghouse 3-loop PWR-type reactor operated by TVA. The reactor core consists of 193 17×17 fuel assemblies, having a fuel stack height of 365.76 cm, each with 264 fuel rods and 25 guide/instrumentation tubes. Fig. 1 shows that the reactor core has three different batches, 2.11 %, 2.62 %, and 3.11 %, with Pyrex burnable absorber cluster assemblies. There are 57 total rod cluster control assemblies (RCCAs), divided into 8 different banks as shown in Fig. 2.

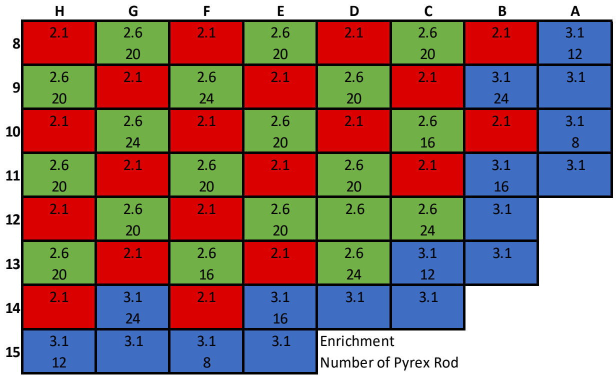

Fig. 1. Watts Bar Unit 1 Cycle 1 Reactor Configuration (Quarter Core Symmetry)

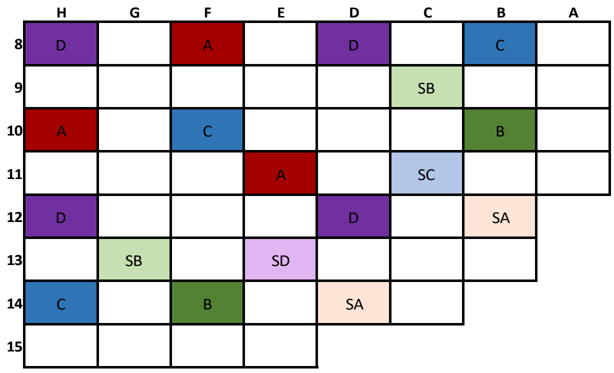

Fig. 2. Watts Bar Unit 1 Cycle 1 Reactor Core Control Bank Core Configuration (Quarter Geometry)

2.2 STREAM3D WB1C1 Reactor Core Modelling

STREAM3D uses a 72-group multi-group neutron cross-section library created by combining ENDF/B.VII.1 and JENDL4.0. STREAM3D solves transport neutron equation based on 3D/MOC. Furthermore, STREAM3D uses pin-based pointwise energy slowing down equations for resonance treatment to obtain more accurate results. In this study, STREAM3D automatically divided each axial plane by less than 3 cm. Thus, more accurate solutions and detailed core power maps can be obtained in this way. STREAM3D also have the capability of modeling all core structure such as spacer grids, baffle, barrel, etc. STREAM3D used 0.05 cm ray spacing, 48 azimuthal angles, and 6 polar angles for a numerical solution in all cases. Also, STREAM3D has the capability of using OpenMP to accelerate simulation. [1]

2.3 Exercise 1: Validation of Cycle 1 Standalone 3-D Neutronics Model at HZP Conditions

Exercise 1 of Watts Bar Unit 1 Cycle 1 consists of ZPPT tasks at beginning of the cycle (BOC) under HZP conditions. Benchmark specification provides measured data and high-fidelity MC code KENO-VI results to make comparisons for criticality test, Control Element Assembly (CEA) group worth, inverse boron worth (IBW), and isothermal temperature coefficient (ITC). Table 1 shows that STREAM3D has remarkable performance and satisfied all acceptance criteria against all given cases. Criticality test results between STREAM3D and KENO-VI were less than 100 pcm as shown in Table 2. As the Control Rod Bank D is used to control criticality throughout the depletion cycle with soluble boron in the coolant, Control Rod Bank D step-by-step and integral worth graphs were plotted as shown in Fig. 3 and Fig 4., respectively. RCCAs are composed of 230 steps corresponding to a 365.125 cm active poison region. Control Rod Bank D step-by-step calculation was made based on a ten percent insertion process, on the other hand, this control bank type integral curve has been plotted by making a ten percent withdrawal process. Control Bank D step-by-step and integral worth values agree with values from KENO-VI within ±0.2 pcm and ±8 pcm.

2.4 Exercise 2: Verification of Cycle 1 Multi-physics Steady State Model for HFP Conditions

This exercise uses multi-physics calculations under Hot Full Power conditions to observe critical boron concentration, radial assembly power distribution, and radial assembly channel coolant exit temperatures. Only the Bank D partial (215 steps) is inserted among all RCCA banks. Equilibrium xenon condition, transient samarium, and thermal expansion are implemented across the quarter reactor core model. Since any data is

Table 1. Watts Bar Unit 1 Cycle 1 CRW, ITC and IBW

Case	Group	Measured	STREAM3D	Diff.*	Rel. Err. [%]**	Acceptance Criteria***
ITC (pcm/°C)	ARO	-3.91	-6.01	-2.1	53.78%	≤ ±9 pcm/°C
Inverse Boron Worth (ppm/pcm)	ARO	-0.093	-0.098	-0.005	5.52%	±0.015 ppm/pcm
CEA Group Worth	A	843	895.72	-52.72	6.3%	±15% or ±100 pcm
	B	879	879.82	-0.82	0.1%	
	C	951	984.30	-33.30	3.5%	
	D	1342	1385.33	-43.33	3.2%	
	SA	435	435.49	-0.49	0.1%	
	SB	1056	1066.04	-10.04	1.0%	
	SC	480	500.56	-20.56	4.3%	
	SD	480	500.56	-20.56	4.3%	
	Total	6467	6647.82	-180.82	2.8%	

* (Measured – ST3D), ** (Measured – ST3D)/Measured*100, ***[6]

Table 2. Watts Bar Unit 1 Cycle 1 Critical Control Rod Position

Critical Control Rod Position						
Case	**Boron Concentration (ppm)**	**Bank D Position**	**Fully Inserted Bank**	**STREAM3D (keff)**	**KENO (keff)**	**Difference* (pcm)**
1	1285	167	ARO	0.999010	0.99990±0.00001	89.10
2	1291	230	ARO	0.999450	1.00032±0.00001	87.02
3	1170	97	Bank A	0.997930	0.99880±0.00001	87.29
4	1170	113	Bank B	0.998420	0.99936±0.00001	94.21
5	1170	119	Bank C	0.998160	0.99904±0.00001	88.25
6	1170	18	Bank D	0.998220	0.99908±0.00001	86.23
7	1170	69	Bank SA	0.998040	0.99902±0.00001	98.29
8	1170	134	Bank SB	0.998480	0.99932±0.00001	84.19
9	1170	71	Bank SC	0.998090	0.99898±0.00001	89.26
10	1170	71	Bank SD	0.998060	0.99898±0.00001	92.27

* (KENO – ST3D)

Fig. 3. Control Bank D Step Worth

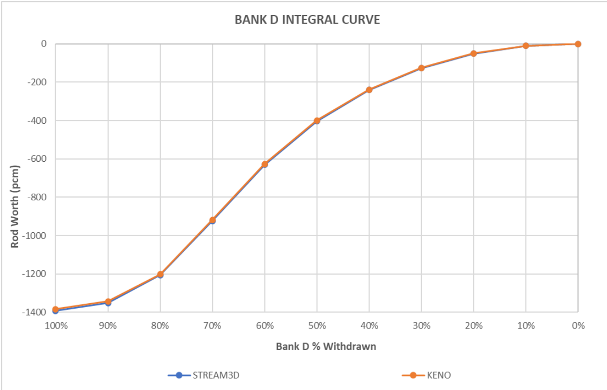

Fig. 4. Control Bank D Integral Worth

not provided for this exercise in the benchmark, STREAM3D radial assembly power distribution and coolant exit temperature maps were compared to high-fidelity MC code MC21-CTF code [5]. CBC differences between measured data and STREAM3D were observed at 4.15 ppm, which satisfied acceptance criteria [6] with great accuracy shown in Table 3. As can be seen from Fig. 5. And Fig. 6., STREAM3D radial power and coolant exit temperature roof mean square (RMS) is ± 1.10% and ± 0.25% compared to MC21-CTF results.

2.5 Exercise 3: Validation of Cycle 1 Multi-physics Depletion Model

The last exercise of this paper is to calculate CBC values of the WB1C1 reactor core during cycle 1 depletion. STREAM3D was run with thermal expansion transient samarium, equilibrium xenon, and critical boron concentration searching options with the quarter core model. STREAM3D was run 26 burnup points for simulation as given in the OECD benchmark publication. However, CBC values provided by the CASL publication consist of a very detailed power profile with 50 burnup points during the cycle. Even if CASL and OECD depletion simulations cannot be compared point by point for this exercise, comparison can still be made in general meaning as shown in Fig. 7. STREAM3D has shown very good agreement within ± 20 ppm differences except for sharp power changes regions and satisfied the acceptance criteria in terms of critical boron concentration.

Table 3. Watts Bar Unit 1 Cycle 1 Critical Boron Concentration at Hot Full Power

	Measured	STREAM3D	Diff.	Err. [%]	Acceptance Criteria
CBC at HFP	854.5 ppm	858.65 ppm	4.15 ppm	-0.49%	±100 ppm

	H	G	F	E	D	C	B	A	
	1.096	1.025	1.095	1.054	1.142	1.058	1.044	0.767	STREAM3D
8	1.118	1.030	1.116	1.056	1.157	1.053	1.049	0.756	MC21-CTF
	-1.96%	-0.50%	-1.85%	-0.23%	-1.30%	0.47%	-0.45%	1.52%	Rel. Diff. (%)
	1.025	1.088	0.982	1.130	1.081	1.146	1.027	0.865	
9	1.030	1.108	0.983	1.148	1.080	1.155	1.012	0.856	
	-0.48%	-1.81%	-0.13%	-1.53%	0.14%	-0.77%	1.49%	1.08%	
	1.095	0.982	1.113	1.074	1.171	1.127	1.052	0.776	
10	1.115	0.983	1.131	1.074	1.184	1.121	1.055	0.765	
	-1.78%	-0.10%	-1.59%	0.00%	-1.13%	0.54%	-0.30%	1.50%	
	1.054	1.130	1.074	1.165	1.082	1.111	1.000	0.642	
11	1.056	1.147	1.074	1.180	1.077	1.118	0.987	0.634	
	-0.15%	-1.49%	0.00%	-1.25%	0.43%	-0.66%	1.37%	1.28%	
	1.142	1.081	1.171	1.082	1.234	0.874	0.900		
12	1.157	1.079	1.185	1.078	1.238	0.865	0.891		
	-1.26%	0.16%	-1.18%	0.40%	-0.30%	1.09%	0.95%		
	1.058	1.146	1.127	1.111	0.874	0.875	0.616		
13	1.054	1.156	1.122	1.119	0.865	0.866	0.607		
	0.41%	-0.84%	0.45%	-0.74%	1.04%	1.12%	1.43%		
	1.044	1.027	1.052	1.000	0.900	0.616			
14	1.049	1.013	1.057	0.988	0.892	0.608			
	-0.50%	1.40%	-0.43%	1.26%	0.84%	1.37%			
	0.767	0.865	0.776	0.642					
15	0.756	0.857	0.765	0.634					
	1.45%	0.99%	1.40%	1.18%					

Max Diff.	-1.96%	Min. Diff	0.00%	RMS	1.10%

Fig.5 Radial Assembly Power Distribution

	H	G	F	E	D	C	B	A	
	330.35	328.15	330.35	329.05	331.65	329.15	328.65	319.65	STREAM3D
8	330.90	327.40	330.80	328.20	332.10	328.20	328.90	318.50	MC21-CTF
	-0.17%	0.23%	-0.14%	0.26%	-0.14%	0.29%	-0.08%	0.36%	Rel. Diff. (%)
	328.15	330.05	326.75	331.35	329.85	331.75	328.15	322.85	
9	327.40	330.50	325.90	331.80	329.00	332.20	326.60	321.90	
	0.23%	-0.14%	0.26%	-0.14%	0.26%	-0.14%	0.47%	0.30%	
	330.35	326.75	330.85	329.65	332.55	331.25	328.95	319.95	
10	330.80	325.90	331.30	328.80	333.00	330.30	329.20	318.70	
	-0.14%	0.26%	-0.14%	0.26%	-0.14%	0.29%	-0.08%	0.39%	
	329.05	331.35	329.65	332.35	329.85	330.75	327.25	315.35	
11	328.20	331.80	328.80	332.90	329.10	331.00	326.00	314.50	
	0.26%	-0.14%	0.26%	-0.17%	0.23%	-0.08%	0.38%	0.27%	
	331.65	329.85	332.55	329.85	334.35	323.25	324.05		
12	332.10	329.00	333.00	329.10	334.20	322.50	323.00		
	-0.14%	0.26%	-0.14%	0.23%	0.04%	0.23%	0.33%		
	329.15	331.75	331.25	330.75	323.25	323.35	314.45		
13	328.20	332.20	330.30	331.10	322.60	322.10	313.60		
	0.29%	-0.14%	0.29%	-0.11%	0.20%	0.39%	0.27%		
	328.65	328.15	328.95	327.25	324.05	314.45			
14	328.90	326.70	329.20	326.00	323.10	313.60			
	-0.08%	0.44%	-0.08%	0.38%	0.29%	0.27%			
	319.65	322.85	319.85	315.35					
15	318.50	321.90	318.80	314.50					
	0.36%	0.30%	0.33%	0.27%					

Max Diff.	0.36%	Min. Diff	-0.04%	RMS	0.25%

Fig.6 Radial Assembly Coolant Exit Temperature

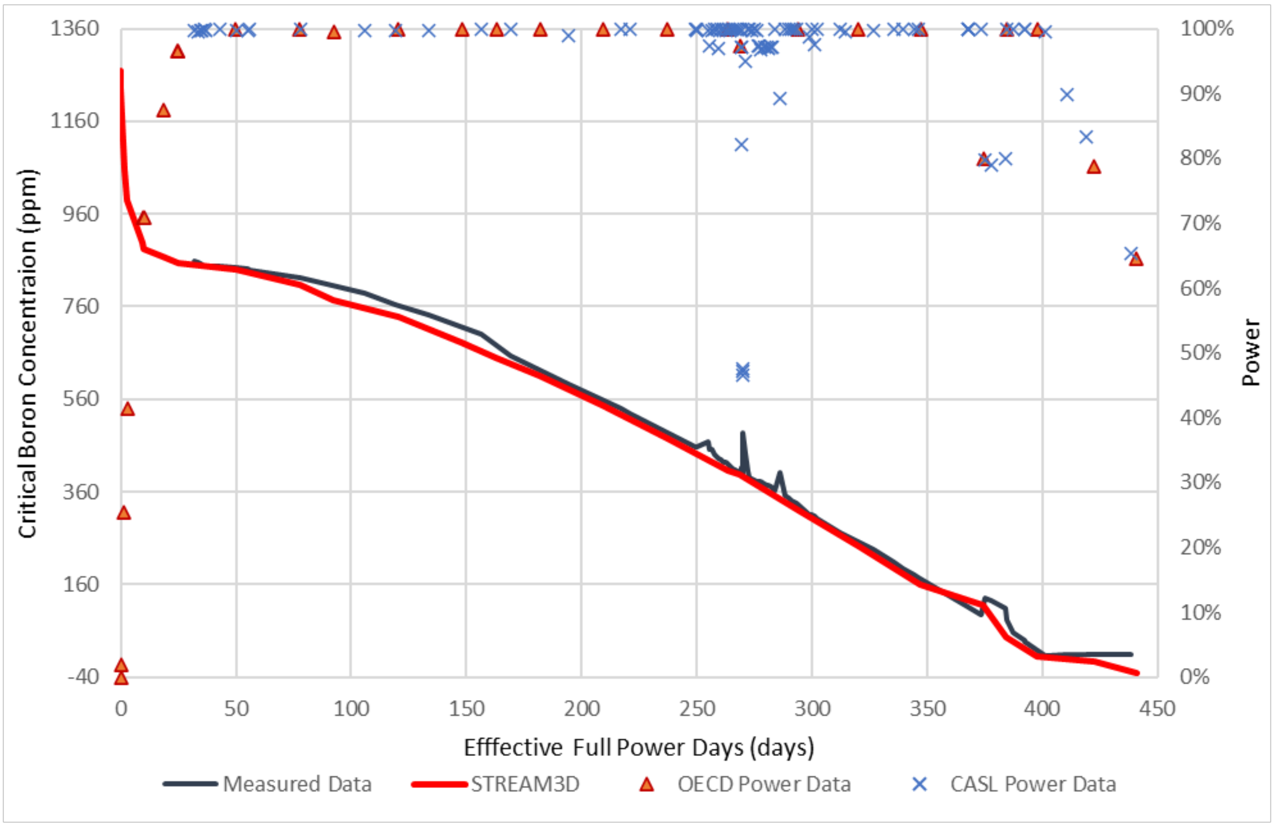

Fig. 7. Watts Bar Unit 1 Cycle 1 Boron Letdown Curve

3. Conclusions

TVA Watts Bar Unit Cycle 1 exercises were simulated by the new direct transport code STREAM3D to be evaluated in terms of various ZPPT core stand-alone transport neutronics cases, multi-physics HFP cases, and depletion cycle CBC based on initial core loading. STREAM3D was compared with measured plant data, high-fidelity MC codes KENO-VI, and MC21-CTF results. All STREAM3D results satisfied the acceptance criteria with good consistency. It can be concluded that STREAM3D generates high-fidelity results by showing excellent performance in both stand-alone and multi-physics calculations for the large-scale PWR reactor.

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