Modeling of Removable Burnable Poison Rods in STREAM/RAST-K Two-step PWR Analysis Code

Anisur Rahman, Jiwon Choe and Deokjung Lee
Department of Nuclear Engineering, Ulsan National Institute of Science and Technology
50 UNIST-gil, Ulsan, 44919, Republic of Korea
**Corresponding author: anisur@unist.ac.kr, deokjung@unist.ac.kr*

1. Introduction

The use of burnable poisons (BP) rods or burnable absorbers (BA) as a replacement of soluble poisons gives a precious function in nuclear fuels. A higher concentration of boron content in moderator makes a positive moderator temperature coefficient (MTC) in PWR. To reduce the boron content and to avoid positive MTC in PWR, the use of BP or BA might be one of the solutions. It is also negotiated with the excess reactivity, smooth the flux, and the neutron spectrum will be hardened, hence yield enlarged core lifetime without any reduction in the safety of the reactor [1]. The rate of burnout can be adjusted by BA configuration in the fuel or assembly. For instance, dense lumps of BA can deplete slower than tinny layers due to self-shielding.

The nuclear fission chain reaction releases a tremendous amount of energy. To be controlled, this energy a predictable manner required. BAs materials are utilized to governor these nuclear chain reactions in an expectable way. These materials have higher neutron absorber cross section and are considered one of the most important tools for nuclear reactor safety. In PWR fuels, generally two types of BAs are used: Integral burnable absorbers (IBAs) and Burnable poison rods (BPRs) [2]. IBAs are fixed, whereas BPRs are removable. In IBAs, Neutron-absorbing materials such as gadolinia (Gd_2O_3) or erbia (Er_2O_3) are directly mixed in a selected fuel rod location with the uranium dioxide (UO_2) fuel within an assembly. BPRs, however, are rods containing neutron-absorbing materials that are inserted into the PWR assembly guide tubes. The Westinghouse has manufactured two main types of BPRs: Pyrex Burnable absorber assemblies (BAAs) and Wet annular burnable absorbers (WABAs). After all, both categories of BAs can be employed to control nuclear reactor core reactivity and local power peaking with optimization of fuel utilization. Over-all, BAs are designed to function during the first cycle of irradiation of a fresh, unirradiated fuel assembly. After one cycle of irradiation, the BPRs are certainly detached from the fuel assembly and permitting primary coolant to occupy the guide tube volume displaced by the BPRs. On the other hand, IBA rods keep in the fuel assembly throughout its lifetime and its usually account for a small reactivity penalty at the end of life, due to incomplete consumption of the neutron-absorber material.

In this paper, only the uses of BAAs inside the core. The BAA BPRs utilize borosilicate glass (B_2O_3-SiO_2 with 12.5 wt% B_2O_3) in the form of Pyrex tubing as a neutron absorber with a void central region and 304 stainless steel cladding material. The STREAM/RAST-K 2.0 (ST/R2) [3,4] is a two-step neutronics core analysis code system for pressurized light water reactor. STREAM, A lattice physics code and RAST-K, a nodal diffusion code have been developed by computational reactor physics and experiment laboratory (CORE) in Ulsan National Institute of Science and Technology (UNIST). This neutronics code (ST/R2) has a platform of coupling with thermal/hydraulic and fuel performance code [5].

2. Methods and Results

2.1 STREAM/RAST-K Code System

ST/R2 code [4] package have a lattice code STREAM (Steady state and Transient REactor Analysis with Method of characteristics) with nodal diffusion code RAST-K. Another connecting code STORA (STREAM TO RAST-K 2.0) is used to make STREAM output file to RAST-K input style (two group constants). Two-dimensional neutron transport equation solves in STRAM with higher accuracy of effective multiplication factor (k_{eff}) within ±100 pcm differences and ±0.1% differences in pin power distribution compared to the Monte Carlo code results [4]. On the other hand, Multi group unified nodal method (UNM) with multi group coarse mesh finite difference (CMFD) acceleration used in RAST-K 2.0 to perform both steady state and transient calculations in a three-dimensional core.

2.2 Single Fuel Assembly

In order to see the performance of BAAs lattice assembly with STREAM, two single fuel assemblies with 12 and 24 BPRs are selected as test models. Fuel temperature and moderator density are 600 K and 0.743 g/cc, respectively. Assembly technical specification and reference solutions are taken from VERA core physics benchmark progression problem [6]. STREAM results are summarized in *Table I*. In the table, 2E (12 BPRs) and 2F (24 BPRs) problem shows ±100 pcm differences of k_{eff} and ±0.1% differences in pin power distribution compared with the reference.

Table I: STREAM single fuel assembly results

Problem	k_{eff}		Pin Power Dist. Diff.[b]	
	k_{eff}	Diff. (pcm)[a]	PW. (%)	Max. (%)
2E	1.06936	-26	0.09	0.25
2F	0.97606	4	0.08	0.28

[a] Difference = (k_{eff} - $k_{eff}^{ref.}$) $\times 10^{05}$
[b] Difference of pin power: PW.: power weight difference; Max.: the maximum difference.

2.3 Westinghouse two-loop plant

In this section, commercial Westinghouse PWR results are shown which core design based on burnable poison rods. It is two-loop PWR and the core has 121 fuel assemblies with 14×14 fuel rod configurations. The quarter core depicts in Fig. 1. Alphabetic letter and number indicate different fuel assembly enrichment and identification (not actual), respectively. *Table II* shows the assembly wise burnable poison rods loading history. One significant information for all the BPRs assemblies that its remove after once burned. At this cycle (three assemblies in quarter core) depleted BPRs is used inside fuel assemblies.

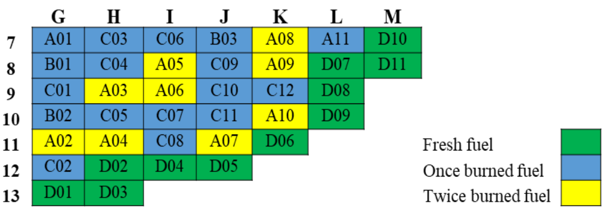

Fig. 1. Core loading configuration.

Table II: Fuel assembly burnable poison rods loading history

Fuel ID	Description
A03, A05	First cycle 12 BPRs used and then remove after once burned.
A04	First cycle 08 BPRs used and then remove after once burned.
A01, A11	First cycle 12 BPRs used and then remove after once burned.
B02, B03	First cycle 08 BPRs used and then remove after once burned.
C04	First cycle without BPRs and now 16 depleted BPRs inserted.
C07, C10	First cycle without BPRs and now 12 depleted BPRs inserted.
others	Normal fuel assemblies without BPRs.

The analyzed reactor core is at equilibrium xenon (Eq Xe), hot full power (HFP) with all rod out condition (ARO) and the reference data is from the nuclear design report (NDR). Fig. 2 shows boron letdown curves at burnup. It is observed that the maximum and minimum difference are found at 0.15 MWd/MT and 6.0 MWd/MT respectively. The maximum difference was -35.66 ppm compare to NDR. The radial assembly power distributions at BOC, MOC and EOC are shown in Fig. 3, 5, and 7. The maximum root mean square (RMS) error was initiate at EOC and the value was 1.67. it shows maximum -3.13, -3.51 and -4.55 % relative errors at BOC, MOC and EOC.

The assembly's burnup distribution at the radial direction is shown in Fig. 4, 6, and 8. it shows maximum -5.34, -3.53 and -3.34 % relative errors at BOC, MOC and EOC and with RMS errors 2.05, 1.30 and 1.26, respectively.

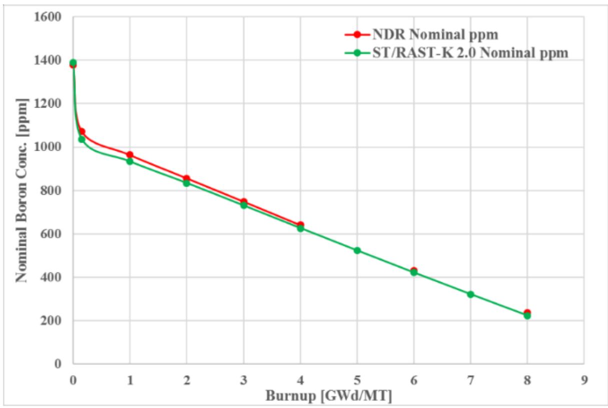

Fig. 2: Boron letdown curves.

	G	H	I	J	K	L	M
7	1.190	1.206	1.162	0.830	0.943	1.127	0.867
	0.84	-0.52	-0.19	-2.50	0.74	2.84	0.34
8	0.934	1.137	0.963	1.089	1.007	1.225	0.718
	-2.65	-0.65	0.76	-0.83	1.25	1.19	-2.57
9	1.154	0.975	1.019	1.153	1.184	0.999	
	-0.34	1.53	1.05	-0.27	2.17	0.08	
10	0.889	1.212	1.183	1.182	0.848	0.621	
	-1.04	-0.16	-0.28	1.52	2.54	-0.23	
11	0.986	1.055	1.215	0.857	0.625		
	-0.64	-0.52	1.21	1.46	-0.78		
12	1.148	1.252	1.020	0.631			ST/R2
	-0.70	-0.17	-1.01	-1.85			
13	0.884	0.732					Relative Error (%)
	-2.80	-3.13					RMS= 1.471

Fig. 3: Radial direction assembly wise normalized power distribution and percent relative error against NDR at BOC (0.15 GWd/MT) [Eq Xe, HFP, ARO].

	G	H	I	J	K	L	M
7	11.560	11.900	8.599	16.500	22.183	11.553	0.131
	-1.41	-0.37	-3.54	1.03	-0.58	-1.36	-0.65
8	15.852	7.084	24.043	11.864	21.814	0.185	0.108
	-0.14	-2.66	1.62	-0.47	-0.66	0.73	-3.18
9	8.597	24.001	20.893	10.172	7.375	0.150	
	-2.53	1.48	-0.50	-1.64	-3.99	-0.27	
10	16.509	7.117	10.202	7.458	20.187	0.093	
	0.55	-3.02	-1.05	-1.85	-0.46	-2.16	
11	22.167	22.569	7.388	20.236	0.094		
	-0.60	0.43	-3.94	-0.31	-2.19		
12	11.890	0.189	0.154	0.095			
	-0.35	-0.46	-1.12	-2.63			
13	0.134	0.111					
	-3.55	-5.34					

ST/R2
Relative Error (%)
RMS= 2.055

Fig. 4: Radial direction assembly wise burnup distribution and percent relative error against NDR at BOC (0.15 GWd/MT) [Eq Xe, HFP, ARO].

	G	H	I	J	K	L	M
7	1.190	1.194	1.167	0.869	0.966	1.124	0.884
	-0.02	-1.22	-0.59	-3.51	0.38	2.25	-0.42
8	0.950	1.133	0.982	1.099	1.014	1.213	0.736
	-3.30	-1.18	-0.21	-0.79	0.62	1.34	-2.21
9	1.156	0.988	1.021	1.128	1.167	1.002	
	-0.54	0.15	-0.10	1.07	1.94	-0.23	
10	0.910	1.195	1.146	1.159	0.859	0.651	
	-2.25	-0.39	0.35	1.79	2.35	-0.10	
11	0.988	1.038	1.181	0.863	0.661		
	0.20	0.16	1.57	1.95	-1.64		
12	1.118	1.218	1.008	0.654			
	0.21	0.19	-0.79	-2.16			
13	0.882	0.737					
	-1.34	-2.29					

ST/R2
Relative Error (%)
RMS= 1.474

Fig. 5: Radial direction assembly wise normalized power distribution and percent relative error against NDR at MOC (4.0 GWd/MT) [Eq Xe, HFP, ARO].

	G	H	I	J	K	L	M
7	16.153	16.526	13.090	19.786	25.872	15.902	3.510
	-1.06	-0.47	-1.97	0.39	-0.45	-0.22	-0.64
8	19.484	11.451	27.795	16.083	25.713	4.890	2.911
	-0.66	-1.82	1.42	-0.55	-0.44	0.79	-2.24
9	13.048	27.786	24.821	14.547	11.896	4.005	
	-1.94	1.32	-0.35	-0.91	-1.67	-0.28	
10	19.980	11.748	14.665	11.951	23.470	2.538	
	0.48	-1.83	-0.81	-0.37	-0.09	-1.54	
11	25.972	26.598	11.990	23.541	2.562		
	-0.58	0.03	-1.79	0.00	-1.55		
12	16.252	4.944	4.053	2.562			
	-0.40	-0.33	-0.97	-1.93			
13	3.531	2.935					
	-2.38	-3.53					

ST/R2
Relative Error (%)
RMS= 1.305

Fig. 6: Radial direction assembly wise burnup distribution and percent relative error against NDR at MOC (4.0 GWd/MT) [Eq Xe, HFP, ARO].

	G	H	I	J	K	L	M
7	1.182	1.181	1.165	0.887	0.978	1.107	0.884
	1.50	0.76	0.45	-0.84	0.22	1.15	-1.59
8	0.962	1.129	0.984	1.103	1.015	1.187	0.746
	-1.24	0.10	1.57	-0.27	0.45	0.25	-3.56
9	1.154	0.988	1.025	1.122	1.157	1.000	
	0.48	1.21	0.45	0.73	1.13	-2.06	
10	0.916	1.182	1.133	1.153	0.876	0.681	
	-0.69	0.63	0.59	1.43	1.53	-3.22	
11	0.989	1.027	1.163	0.877	0.702		
	0.12	0.30	1.45	1.44	-3.22		
12	1.093	1.184	1.000	0.681			
	0.65	-0.31	-2.01	-3.25			
13	0.877	0.742					
	-2.02	-4.55					

ST/R2
Relative Error (%)
RMS= 1.670

Fig. 7: Radial direction assembly wise normalized power distribution and percent relative error against NDR at EOC (8.0 GWd/MT) [Eq Xe, HFP, ARO].

	G	H	I	J	K	L	M
7	20.900	21.279	17.757	23.307	29.762	20.362	7.043
	-0.72	-0.42	-1.52	-0.03	-0.21	0.12	-0.93
8	23.311	15.978	31.736	20.489	29.770	9.688	5.871
	-0.96	-1.34	1.29	-0.52	-0.29	0.56	-2.61
9	17.673	31.746	28.916	19.046	16.542	8.008	
	-1.48	2.44	-0.25	-0.52	-0.73	-0.65	
10	23.638	16.503	19.223	16.575	26.941	5.201	
	0.12	-1.24	-0.46	0.20	0.16	-2.01	
11	29.925	30.726	16.675	27.020	5.287		
	-0.50	0.32	-0.83	0.22	-2.10		
12	20.667	9.741	8.064	5.231			
	-0.27	-0.23	-1.13	-2.27			
13	7.045	5.888					
	-2.14	-3.34					

ST/R2
Relative Error (%)
RMS= 1.262

Fig. 8: Radial direction assembly wise burnup distribution and percent relative error against NDR at EOC (8.0 GWd/MT) [Eq Xe, HFP, ARO].

3. Conclusions

There are several papers about verification of STREAM/RAST-K regarding commercial PWRs. This paper firstly present that STREAM/RAST-K code system can demonstrate perfectly in the second cycle using removable burnable poison rods. It proves that below 5.0% relative error in radial power distribution and RMS error below 2.0 at BOC, MOC and EOC. Furthermore, the burnup distributions also shows good results below 5.0% relative error and RMS error below 2.0 in all the cycle.

4. Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT). (No.NRF-2020M2A8A5025118)

REFERENCES

[1] Farrokh Khoshahval, Shima Sheikh Foroutan, Ahmad Zolfaghari, Hamid Minuchehr, "Evaluation of burnable absorber rods effect on neutronic performance in fuel assembly of WWER-1000 reactor", Annals of Nuclear Energy 87 (2016) 648-658.

[2] Abdelghafar Galahom, "Study of the possibility of using Europium and Pyrex alloy as burnable absorber in PWR", Annals of Nuclear Energy 110 (2017) 1127-1133.

[3] Sooyung Choi, Minyong Park, Youqi Zheng, Chidong Kong, Jiwon Choe, Hanjoo Kim, Kiho Kim, Ho Cheol Shin, Deokjung Lee, Development status of reactor physics code suite in UNIST, in: 11st International Conference of the Croatian Nuclear Society, Zadar, Croatia, June 5-8, 2016, Croatian Nuclear Society, 2016.

[4] Jiwon Choe, Sooyoung Choi, Peng Zhang, Jinsu Park, Wonkyeong Kim, Ho Cheol Shin, Hwan Soo Lee, Ji-Eun Jung, Deokjung Lee, "Verification and validation of STREAM/RAST-K for PWR analysis," Nuclear Engineering and Technology, ISSN 1738-5733.

[5] Hanjoo Kim, Jinsu Park, Jiwon Choe, Jiankai Yu, Deokjung Lee, Multi-physics Coupled Reactor Core Analysis System of RAST-K2.0 with CTF and FRAPCON, in: KNS Spring Meeting, Jeju, Korea, May 16-18, 2018.

[6] T. Godfrey, Vera core physics benchmark progression problem specifications, Revision 4, CASL-U-2012-0131-004, CASL, 2014.