Tri Dasa Mega Vol. 23 No. 1 (2021) 15–20

Jurnal Teknologi Reaktor Nuklir

Tri Dasa Mega

Journal homepage: jurnal.batan.go.id/index.php/tridam

Evaluation of Equilibrium Core Operation of the RSG-GAS Reactor

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ARTICLE INFO

Article history:

Received: 15 December 2020
Received in revised form: 18 January 2021
Accepted: 5 February 2021

Keywords:

RSG-GAS reactor
Reactor operation
Equilibrium core
BATAN-FUEL
In-core fuel management

A B S T R A C T

The Indonesian Multipurpose Reactor, RSG-GAS reactor will accomplish its first lifetime in December 2020. The reactor has been operated in safe and reliable manner for about 33 years since it commenced in operation in 1987 to serve radioisotopes production, NAA, neutron beam experiments, material irradiation, and reactor physics experimental activities as well as training. The paper is intended to evaluate its in-core fuel management that is the conformance between the theory and implementation of the equilibrium core. Evaluation of the reactor operation parameter was carried out for core numbers 91 – 100. The data show that excess reactivity, shutdown reactivity and control rod reactivity have no significant difference at each core. The result shows that the BATAN-FUEL accurately determine the equilibrium core and its fuel loading pattern.This in-core fuel management of the RSG-GAS reactor supports the safety of reactor operation.

1. INTRODUCTION

The RSG-GAS reactor was designed as a multipurpose reactor with a nominal power of 30 MW, located in the Science and Technology Research Center, PUSPIPTEK area, Serpong, Tangerang. It is operated by the Center for Multipurpose Reactor, National Nuclear Energy Agency of the Republic of Indonesia (PRSG-BATAN).The reactor commenced to the formal operational status in August 1987. At nominal power, the reactor produces thermal neutron flux in the order of 10^{14} neutron $cm^{-2}s^{-1}$[1]

The in-core fuel management plays an important role because it relates the reactor safety and operation cost.[2, 3]. Some research reactors use the equilibrium core technique and some others use the once through core loading technique [4, 5]. As a multipurpose reactor, RSG-GAS provides various facilities for utilization on material testing, radioisotope production, R&D using neutron irradiation as well as training. In order to serve this utilization, the reactor was operated at nominal power for about 25 days per cycle and eight cycles per year. The typical working core or so called equilibrium core has been determined by an in-core fuel management strategy with a loading pattern of 5/1[6, 7]. In every cycle there will be five fuel elements and one control element reaching the discharged burn up (56%) unloaded and changed by the fresh ones (0% burn up).

In-core fuel management of the original loading strategy and operation program was then modified to achieve its optimal utilization and efficient operation of the reactor. The operation program was determined based on the radioisotope production needs[8]. For this purpose the reactor is operated routinely 5 days per week with a power level of 15 MW or the half of the nominal power.

After long operation of 33 years, since its first operation in the year 1987 until 2020 with core numbers 1- 100[9], it is necessary to evaluate its fuel management pattern reactor of the RSG-GAS.

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DOI: 10.17146/tdm.2021.23.1.6150

The purpose of the research is to know whether the 5/1 pattern does not changes of the core operation parameter. For these reasons, the last operation of 10 cores that are no. 91 to 100 will be evaluated. Those parameters are core excess reactivity, shut down reactivity, shut down margin reactivity and control rod reactivity as well. These parameters are very important for the safety of the reactor operation.

2. IN-CORE FUEL MANAGEMENT OF RSG-GAS CORE

The reactor is an open-pool type, cooled and moderated with light water, using the LEU-MTR type fuel element in the form of U_3Si_2-Al dispersion[2]. The reactor core is 60-cm in height with a rectangular cross section, located in the reactor pool 12.45 m under the pool surface. The core configuration is arranged in a 10 × 10 array grid and it consists of 40 standard fuel elements, 8 control elements, 8 AgInCd control absorber; 1 CIP (Central Irradiation Position), 4 IPs (irradiation positions), 5 rabbit systems and other irradiation holes in the reflector region. The reactor core is surrounded by beryllium elements and a beryllium block reflector, as shown in Figure 1. The figure also shows out-core irradiation facilities comprising Power Ramp Test Facility, Neutron Radiography and Silicon Doping Facility as well as Beam tubes.

The heat produced in the core is removed by 2 lines of the primary cooling system. Two shells and tube type heat exchanger and six cooling towers then, dissipate the heat to the atmosphere. Motorized valves located in a tight compartment chamber can isolate the pool. This allows the system to rule out the possibility of a serious loss of coolant accident, which is considered in the safety analysis. Six beam tubes, four radial and two tangential tubes, are available to be used for several purposes. The radial beam tube no.1 is equipped with Xe-loop to produce ^{125}I radioisotope; the tangential beam tube no. 2 is dedicated for neutron radiography; the radial beam-tube no.3 is still unused, beam tubes no. 4 and 6 are used.

The task of in-core fuel management is to determine the operating core configuration for its cycle operation that meets the safety and utilization requirements. The activities cover loading unloading fuel elements to build operating core according to a specific burn up distribution[10, 11]. This specific core configuration shall provide:

a. An adequate excess reactivity for cycle operation during a certain period at full power.
b. Neutron flux distribution in the level required by the user in the irradiation facilities

From the safety point of view, the core configuration shall meet these requirements:

a. Core excess reactivity shall produce shut down margin reactivity greater than 0.5%, at one stuck rod condition.
b. Power distribution shall flat to assure a safe cooling at every point of the fuel element.

The loading – unloading of fuel elements for building core configuration is usually called a loading scheme or loading pattern. The certain or unchanged loading pattern will provide the same core configuration with the same operating parameters for every cycle operation. This stable core configuration is called a typical working core (TWC) or is generally called an equilibrium core (EC). The loading pattern is determined by calculation by a neutron diffusion computer code. The calculation covers core excess reactivity, change of reactivities during cycle including fuel burn up, control rod reactivity and shut down margin reactivities.

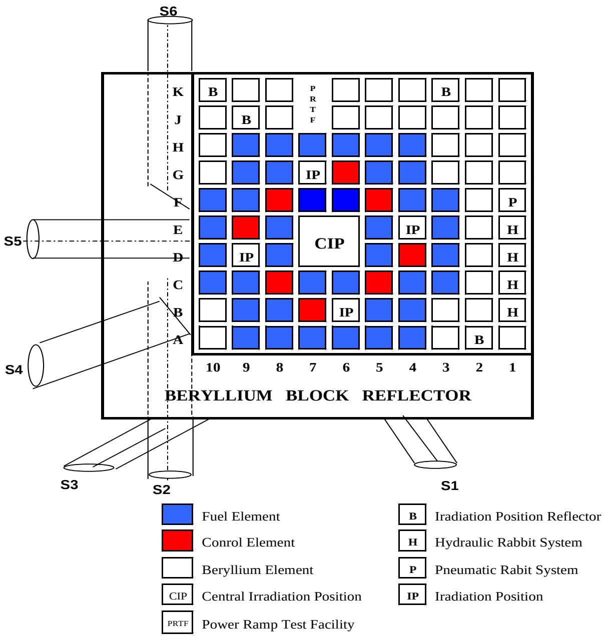

Fig.1. The RSG-GAS core configuration[6]

By BATAN-FUEL[12] computer code, a loading pattern of 5 FE and 1 CE was derived and then imposed to RSG-GAS reactor operation. This loading pattern is intended to obtain the optimal core against its utilization.

The loading pattern 5/1 loading pattern can be briefly summarized as the followings:

Fuel elements are grouped into 8 burn up classes with difference of 7 %, namely group no. 1,2,3,…..8, for burn up class 0 % (fresh), 7%, 14%, 21%, 28%, 35%, 42%, and 49%. The burn up of 56% is achieved at the end of cycle, so this is the discharged burn up. Each burn up class has 6 fuel elements members, 5 FEs and 1 CE.

At BOC the operating core of the reactor is built by 48 fuel elements distributed symmetrically in the core as shown in Figure 2. with burn up classes 1 - 8.

The average burn up of core fuel is 23.8 %.

Operation cycle length is designed to be 600 MWD instead of 750 MWD which consumes an average burn up of 7% of fuel core.

At EOC, the burn up classes of the fuel elements increases 7%, with an average burn up of 30.3%, six elements i.e. 5 FE and 1 CE which reach discharge burn up group of 56%, then taken out and replaced by the fresh FE and CE ones.

H		FE 1	FE 2	FE 5	FE 4	FE 5	FE 1	
G		FE 3	FE 8	**IP**	CE 7	FE 7	FE 6	
F	FE 2	FE 2	CE 3	FE 6	FE 8	CE 2	FE 7	FE 1
E	FE 3	CE 6	FE 4	**CIP**		FE 6	**IP**	FE 3
D	FE 5	**IP**	FE 8			FE 4	CE 5	FE 5
C	FE 2	FE 7	CE 1	FE 7	FE 6	CE 4	FE 3	FE 1
B		FE 6	FE 8	CE 8	**IP**	FE 8	FE 4	
A		FE 1	FE 7	FE 4	FE 5	FE 3	FE 2	
	10	**9**	**8**	**7**	**6**	**5**	**4**	**3**

Fig. 2. Core burn-up distribution of RSG-GAS according to loading pattern 5/1, at BOC

Reactivity balance aspects are presented in Table 1[7]. It shows that the two both loading patterns meet the safety limit.

Table 1. Reactivity balances for loading pattern 5/1.

	Pattern 5/1
Cycle length, FPD	20
Energy release, MWD	600
Reactivity balance:	
Hot to cold, %	0.6
Equilibrium xenon poisoning, %	3.6
Burn up, %	2.5
For experiments, %	1.0
For Operation manipulation, %	2.2
Core excess reactivity, %	9.8
Control rod worth, %	- 13.8
Shutdown reactivity, %	- 4.0
Stuck rod reactivity, max., %	- 2.9
Shutdown margin, %	1.1

By loading pattern 5/1, a stable or constant scheme of fuel refreshing and reshuffling has been derived. After completing of the cycle operation, the reactor is in the shut down condition stage for fuel reshuffling to build the next BOC core configuration. According to the loading pattern 5/1 fuel elements at positions G-8, F-6, D-8, B-8, B-7 and B-5 are taken out as discharged fuel. Then fuel elements are shifted following scheme as shown in Table 2. For example, FE at H-9 moves to F-10. Five new FE's and 1 CE are inserted to positions B-9, C-3, C-8, F-3, H-4 dan H-9. It is noted that positions B-7, C-8, C-5, D-4, E-9, F-8, F-5 dan G-6 are for CE.

Table 2. Fuel element reshuffling at RSG-GAS core by loading pattern 5/1[6]

From	To	From	To	From	To
H-9	F-10	F-5	F-8	C-7	B-8
H-8	C-4	F-4	F-6	C-6	G-5
H-7	F-7	F-3	C-10	C-5	D-4
H-6	D-10	E-10	B-4	C-4	D-5
H-5	E-5	E-9	G-6	C-3	H-8
H-4	F-9	E-8	D-3	B-9	C-9
G-9	E-8	E-5	A-8	B-8	Out
G-8	Out	E-3	A-7	B-7	Out
G-6	B-7	D-10	G-4	B-5	Out
G-5	G-8	D-8	Out	B-4	A-6
G-4	C-7	D-5	H-5	A-9	A-4
F-10	G-9	D-4	E-9	A-8	B-5
F-9	A-5	D-3	C-6	A-7	H-7
F-8	C-5	C-10	E-3	A-6	B-9
F-7	F-4	C-9	D-8	A-5	H-6
F-6	Out	C-8	F-5	A-4	E-10

4. RESULTS AND DISCUSSION

Based on the calculated loading pattern, the core is then loaded by fuel element (FE) and control element (CE). The control element is a fuel element containing fork absorber blade as a control rod. Afterward, control rod calibration should be done to get the reactivity worth of the control rods as a function of control rod positions. Control rod calibration of one control rod of the RSG-GAS reactor of core 91 is presented in Figure 3. This S-curve was derived at the critical condition at low power and control rod position of 284 mm. From the curve, we get the control rod worth reactivity, core excess reactivity and shut down reactivity. When we have more than one control rod, those values are obtained from the summation of the individual control rod curve. In the case of the RG-GAS reactor there are eight control rods. It means that by doing control rod calibration, we can generate a reactivity balance of the reactor core, i.e., the control rod worth reactivity, core excess reactivity and shut down reactivity as well as shut down margin reactivity. The shut down margin reactivity is derived by subtracting the shut down reactivity by the maximum value of a control rod worth. When the safety conditions, shut down margin and core excess reactivity are fulfilled, the reactor can be operated for the cycle operation to serve its utilization.

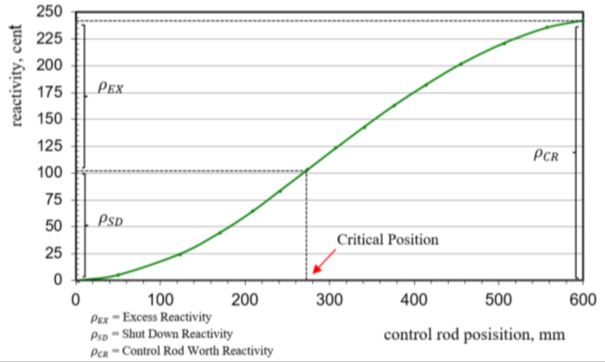

Fig.3. S-curve of control rod calibration results

The methodology of evaluation is by comparing the theoretical fuel management (calculation) and the implementation results of the reactor operation. The comparison covers the main parameter of the cycles operation such as number of fuel loading, reactivity balance and energy release. The experimental reactivity balance is obtained from the results of control rod calibration at each beginning of the cycle of 10 cores that are core number 91 to 100.

By now, until core no. 100, the reactor has been operated for totally 626.37 MWD. In the first 8 years of the operation period, the activities were concentrated on the commissioning of the reactor, installation of the new equipment in the reactor and also the learning period of the personnel. From this figure, it can be seen that from 1995, the reactor was successfully operated around 5000 h/year at the nominal power level. A loading pattern of 6/1 was applied and the reactor has been operated for 6 to 8 cycles/year. Since the year 1998, reactor operation was conducted by the new loading pattern of 5/1. According to this pattern, the reactor has been operated for 540 – 600 MWD. Upon optimization of the fuel availability, user requirement as well as efficiency, the reactor was operated at the power level of 15 MW, up to max. 4 cores cycles annually. The reactivity data of operation cycles of 10 operating cores, namely core no. 91 to 100 covering a period of 16 April 2016 to February 2020 have been collected and summarized in Table 3. It is noted that the ρ is the reactivity with the unit of % (Δk/k).

Table 3. Cycle operation data of the RSG-GAS Reactor

Core number	CR pos BOC (cold, clean)	CR pos EOC (hot, poisson)	Energy per cycle (MWD))	Fuel loading (FE/CE)	ρ CR Total (%)	ρ Core excess (%)	ρ Shut down (%)	ρ CR max (%)	ρ Shut down margin (%)
1	2	3	4	5	6	7	8	9	10
91	278/278	582/580	640.22	5/1	- 13.20	+ 7.29	- 5.91	- 1.86	- 4.05
92	292/292	561/565	615.83	5/1	-13.55	+ 6.95	- 6.60	- 1.92	- 4.68
93	287/287	554/556	625.05	5/1	- 13.38	+ 7.87	- 5.51	- 1.87	- 3.64
94	282/282	540/538	625.00	5/1	- 13.01	+ 6.99	- 6.02	- 1.88	- 4.14
95	280/280	548/537	625.64	5/1	-12.92	+ 7.04	-5.88	- 1.86	- 4.02
96	276/276	555/553	625.01	5/1	-13.02	+ 7.21	-5.81	- 1.85	- 3.96
97	275/275	511/511	625.00	5/1	-12.91	+ 7.10	-5.81	- 1.84	- 3.97
98	286/286	541/546	625.01	5/1	-13.20	+ 7.00	-6.20	- 1.85	- 4.35
99	284/284	546/547	625.08	5/1	-13.27	+ 7.16	-6.12	- 1.90	- 4.22
100	284/284	561/554	626.37	5/1	-13.44	+ 7.13	-6.32	- 1.84	- 4.48

From Table 3, some important characteristics of the RSG-GAS reactor operation can be observed. The reactor was operated for the last ten cores with nearly the same cycle length producing energy of of around 625 MWD from 615 to 640 MWD (column 4) and a loading pattern of 5/1 (column 5). Each cycle was loading by fuel element which produces excess reactivity in the amount of around 7 % that is between 6.95 and 7.87 (column 7) and provides similar shut down margin reactivity of around 4 % from 3.64 to 4.68 (column 10). From the control rods' positions point of view, it shows that for a cycle operation it starts from position of around 280 mm, from 275 to 292 mm (column 2) at BOC and of around 550 mm, from 511 to 582 mm (column 3) at the end of cycle. All of those relatively stable cycle parameter show that the loading pattern 5/1 is a very good strategy to build the equilibrium core which proves the typical working core of the RSG-GAS reactor from the beginning of operation phase until recently at the end phase of operation, for 22 years from the years of 1998 to 2020.

Reactivity values of the individual control rod of core number 91-100 are presented in Table 4. Measurement has been conducted by pair compensation method, where one control rod at the bottom position and the other one at the upper position and the other 6 control rod at bank position. Based on the result, as shown in Table 4, the reactivity values of the control rod of each core perform no significant change. It means that by implementing a 5/1 pattern of in-core fuel management the RSG-GAS is stable.

Table 4. Result of the control rod reactivity measurement of 8 control rods at core 91-100

Control rod No.	Reactivity (%)									
	Core 91	Core 92	Core 93	Core 94	Core 95	Core 96	Core 97	Core 98	Core 99	Core 100
JDA01	1.5740	1.6314	1.6008	1.5472	1.5855	1.5797	1.5989	1.5702	1.5950	1.6581
JDA02	1.6333	1.6696	1.6639	1.6581	1.6352	1.6428	1.6627	1.6103	1.6218	1.6275
JDA03	1.7939	1.8723	1.8284	1.8284	1.7958	1.8532	1.8398	1.8169	1.8035	1.8360
JDA04	1.7867	1.7825	1.8054	1.6868	1.6849	1.6601	1.5644	1.7557	1.8131	1.7844
JDA05	1.7844	1.7997	1.8437	1.7863	1.7729	1.7710	1.7293	1.8092	1.7557	1.8417
JDA06	1.4038	1.4382	1.3885	1.4095	1.3598	1.4306	1.3433	1.4076	1.3904	1.4439
JDA07	1.3770	1.4363	1.3827	1.2087	1.2183	1.2326	1.3311	1.3770	1.3942	1.3847
JDA08	1.8551	1.9182	1.8685	1.8857	1.8647	1.8532	1.8417	1.8513	1.8915	1.8666

5. CONCLUSION

From the conduct of reactor operation and implementation of the loading pattern strategy of 5/1, it shows that the in-core fuel management successfully provided the equilibrium core. The results supports the conduct of operation in a safe manner for optimal utilization with stable parameters and under stable nuclear safety conditions.

ACKNOWLEDGMENT

The authors thank the Head of PTKRN and Dr Syaiful Bakhri for financial support using DIPA in the year 2017 and their cooperation in conducting this research. They also express their thanks to the Head of PRSG for allowing data and staff to conduct this research work.

AUTHOR CONTRIBUTION

Iman Kuntoro, Surian Pinem and Tagor Malem Sembiring are equally contributed as the main contributors of this paper. All other authors read and approved the final version of the paper.

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