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FUEL BURN-UP CALCULATION FOR WORKING CORE OF THE RSG-GAS RESEARCH REACTOR AT BATAN SERPONG

PERHITUNGAN FRAKSI BAKAR TERAS KERJA REAKTOR RISET RSG-GAS DI BATAN SERPONG

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Abstract

The neutronic parameters are required in the safety analysis of the RSG-GAS research reactor. The RSG-GAS research reactor, MTR (Material Testing Reactor) type is used for research and also in radioisotope production. RSG-GAS has been operating for 30 years without experiencing significant obstacles. It is managed under strict requirements, especially fuel management and fuel burn-up calculations. The reactor is operated under the supervision of the Regulatory Body (BAPETEN) and the IAEA (International Atomic Energy Agency). In this paper, the experience of managing RSG-GAS core fuels will be discussed, there are hundred possibilities of fuel placements on the reactor core and the strategy used to operate the reactor will be crucial. However, based on strict calculation and supervision, there is no incorrect placement of the fuels in the core. The calculations were performed on working core by using the WIMSD-5B computer code with ENDFVII.0 data file to generate the macroscopic cross-section of fuel and BATAN-FUEL code were used to obtain the neutronic parameter value such as fuel burn-up fractions. The calculation of the neutronic core parameters of the RSG-GAS research reactor was carried out for U_3Si_2*-Al fuel, 250 grams of mass, with an equilibrium core strategy. The calculations show that on the last three operating cores (T90, T91, T92), all fuels meet the safety criteria and the fuel burn-up does not exceed the maximum discharge burn-up of 59%. Maximum fuel burn-up always exists in the fuel which is close to the position of control rod.*

Keywords: *reactor core, U3Si2-Al fuel, fuel burn up, WIMSD-5B, BATAN-FUEL*

Abstrak

Parameter neutronik dibutuhkan dalam analisis keselamatan reaktor riset RSG-GAS. Reaktor riset RSG-GAS jenis MTR (Material Testing Reactor) digunakan untuk riset dan juga produksi radio isotop. RSG-GAS sudah 30 tahun beroperasi tanpa mengalami kendala yang berarti karena dikelola dengan menggunakan persyaratan yang ketat terutama pengelolaan bahan bakar dan perhitungan fraksi bahan bakarnya karena dioperasikan dibawah pengawasan BAPETAN (Badan Pengawas Tenaga Atom

Nasional) dan IAEA (International Atomic Energy Agency) agar beroperasi sesuai dengan desainnya. Pada makalah ini dibahas pengalaman mengelola bahan bakar teras RSG-GAS dimana ada ratusan kemungkinan penempatan bahan bakar di teras reaktor dan strategi yang digunakan sangat menentukan keselamatan operasinya. Namun berdasarkan perhitungan yang teliti dan pengawasan yang ketat bahan bakar tidak ada yang salah penempatan. Perhitungan dilakuan pada teras kerja RSG-GAS dengan menggunakan paket program komputer WIMSD-5B dengan mengunakan ENDFVII.0 data file untuk menggenerasi tampang lintang makroskopik bahan bakar dan BATAN-FUEL untuk memperoleh nilai parameter neutronik salah satunya yaitu fraksi bakar dari keseluruhan bahan bakar. Perhitungan parameter neutronik teras reaktor riset RSG-GAS dilakukan untuk bahan bakar U3Si2-Al dengan tingkat muat 250 gram dengan strategi teras setimbang. Hasil perhitungan menunjukan bahwa pada ke tiga teras terakhir yang beroperasi (T90, T91, T92) menunjukkan bahwa semua bahan bakar memenuhi kriteria keselamatan dan fraksi bakar bahan bakar tidak ada yang melebihi fraksi bakar maksimum yaitu 59%. Fraksi bakar maksimum selalu terdapat pada bahan bakar yang dekat dengan posisi batang kendali.

Kata Kunci: *teras reaktor, bahan bakar U3Si2-Al, fraksi bakar, WIMSD-5B, BATAN-FUEL*
PACS: 28.50.Dr, 28.41.-i, 28.41.Vx

I. INTRODUCTION

Indonesia has 3 old research reactors. One of the newest reactors is the RSG-GAS reactor (Multipurpose Reactor G.A. Siwabessy). It has been operating for 30 years with a nominal power of 30 MWth. Meanwhile, 2 (two) other research reactors, TRIGA type, Kartini reactor (Yogyakarta) and TRIGA 2000 (Bandung) reactor will end their operating license period within 2016-2020. The TRIGA Bandung reactor has just obtained an operating license from Bapeten (Badan Pengawas Tenaga Nuklir) while RSG-GAS reactor is still struggling to obtain an operating license from Bapeten. One of the requirements made by Bapeten to obtain an operating license shall be to evaluate or assess operation safety of the reactor. Therefore, evaluation or assessment of RSG-GAS reactor operation is conducted by calculating the burn-up fuel fraction that indicates fuel integrity is still feasible to be used up to maximum fuel burn-up. Maximum fuel burn-up fraction according to RSG-GAS core design, based on SAR (Safety Analysis Report) document is 56%, but after being replaced with silicide fuel, Bapeten allow up to 59% [1].

One of the duties and functions of PTKRN-Batan is to support the RSG-GAS reactor to operate properly and safely for 250 grams silicide fuel. RSG-GAS reactor needs to examine the aging of each system, its components and its structure. Aging management aims to make every system, structure and component available in RGS-GAS, so the aging of each system can be prevented and found since early damage and repair. Fuel is one of the most important components in the reactor core so it should always be checked in both visually and with a gamma camera. Each dismantling fuel at the end of the cycle always checks and records the existence of fuels and control rods. The integrity of the fuel inside and outside of the core must be checked and recorded, including its condition and existence [2]. The history of these fuels is important in fuel management and it aims to know the state of each fuel as early as possible that is accurate in both the condition and the fuel burn-up.

To determine the fuel burn-up by measurement which consists of 48 fuels for each core is very difficult and also time-consuming, hence it is conducted by analyzing the calculation results. Calculation of RSG-GAS core fuel management should be done properly and accurately or it will cause damage and problems arise in the fuel. One of the supporting analysis to obtain the RSG-GAS reactor operation license from Bapeten is the evaluation of its core fuel burn-up fraction. Evaluation or assessment in this paper only conducted to the last 3 cores, specifically on the T90, T91 and T92. Calculations were performed using the WIMSD-5B [3] and BATAN-FUEL computer codes [4]. Calculations with WIMSD-5B code is based on neutron transport method while BATAN-FUEL is based on 2-dimensional neutron diffusion method. Generation of cross-sectional fuel with a 17-step fuel burn-up fraction is made using ENDF / B-VII.0 nuclear data [5].

In-core Fuel Management

The main objective of core fuel management is to achieve a high fuel discharge burn-up according to the design and form a safe and efficient core configuration to operate at its nominal power [6]. This requires a fuel management strategy plan within the core that includes the establishment of core configuration, the determination of fuel burn-up fraction, the length of the operating cycle, the fuel input pattern and its safe operation.

The objectives and terms of re-fueling periodically into the core are:

a. to increase the amount of reactivity in the core (within safe limits) in order to operate at full power during certain operating cycle lengths.
b. to get a distribution of heat generation evenly in the core.
c. to ensure that the neutron flux in the reactor protection system does not exceed the limit value.
d. to ensure that the neutron flux in the irradiation position is maintained at the desired level.

There are several types of fuel loading schemes used in fuel management at research reactors. However, RSG-GAS uses an out-to-center loading scheme, fresh fuel inserted in the outer edge of the core, followed by a shift to the center. The RSG-GAS core has a center irradiation position, the fuel that has been burned is determined based on the calculation of the core management to obtain a core configuration that meets the safety criteria. Then the fuel which already has an average burn-up of 48 or 56% at the end of the cycle, is removed as spent fuel.

Fuel Burn-up

If a reactor is operated with only one isotope fuel N_F, example U^{235}, then the lost fuel rate for isotope U^{235} is [7]:

$$\frac{\partial N_F}{\partial t} = -N_F\left(\vec{r},t\right)\sigma_a^F\phi\left(\vec{r},t\right) \quad (1)$$

in which:

$N_F\left(\vec{r},t\right)$ is isotope density at $\vec{r}$ position and t time (cm^{-3})

σ_a^F is fuel sigma absorbtion (cm^2)

$\phi\left(\vec{r},t\right)$ is neutron flux ($n\ cm^{-2}\ s^{-1}$)

If neutron flux is known, then lost fuel rate $N_F(\mathbf{r},t)$ is:

$$N_F\left(\vec{r},t\right) = N_F\left(\vec{r},0\right)\exp\left[-\sigma_a^F\int_0^t\phi\left(\vec{r},t'\right)dt'\right] \quad (2)$$

where:

$$\phi(\vec{r},t)=\int_0^t \phi(\vec{r},t')dt' \quad (3)$$

Eq. (2) becomes

$$N_F(\vec{r},t)=N_F(\vec{r},0)\exp\left[-\sigma_a^F\phi(\vec{r},t)\right] \quad (4)$$

If the power of reactor is maintained at a certain level at $P(\vec{r},0)$, so that:

$$P(\vec{r},t)=w_a N_F(\vec{r},t)\sigma_a^F=P(\vec{r},0) \quad (5)$$

with w_a is the energy released by every neutron absorbed by the fuel. When the value of w_a is,

$$w_a=\frac{\sigma_f^F}{\sigma_a^F}\gamma \quad (6)$$

So that Eq. (1) becomes,

$$\frac{\partial N_F}{\partial t}=-N_F(\vec{r},t)\sigma_a^F\phi(\vec{r},t)=\frac{P(\vec{r},0)}{w_a} \quad (7)$$

The amount of lost fuel rate is expressed as fuel burn-up with the unit as % (lost of ^{235}U isotope), MWD (Mega Watt Day) or MWD/ton HM (heavy metal).

Equilibrium Core Calculation Procedure

The RSG-GAS core is said to be an equilibrium if all of the core parameters remain unchanged from one cycle to next cycles [8]. The following is presented in an equilibrium search procedure using neutron diffusion method. The isotope density at Eq. (1) can be expressed with isotope density vector $N(\vec{r},t)=\left[N_1(\vec{r},t),N_2(\vec{r},t),\ ...,N_k(\vec{r},t)\right]^T$ in which k as an index of isotope with amount of total isotope as K and T is expressed as a matrix transform. Thus, the isotope density in the time-dependent can be expressed in first-order differential equations:

$$\frac{\partial}{\partial t}N(\vec{r},t)=T(\phi,\sigma,\lambda)N(\vec{r},t) \quad (8)$$

where ϕ, σ, and λ are expressed as flux neutron (energy and space dependent), sigma absorption, and decay constant, respectively.

The neutron flux distribution used in the eq. (8) is obtained from the calculation of criticality,

$$M(N)\phi=\frac{1}{k_{eff}}F(N)\phi \quad (9)$$

Operator *M* is the migration operator and the loss of neutrons while operator *F* is the neutron production operator.

At the time of loading and shifting of fuel, then,

$$N^{j+1}(r,0)=S^jN^j(r,\tau)+N_{in}^{j+1}(r,0) \quad (10)$$

At eq. (10), *j* and τ are expressed as core cycle index and cycle length of reactor operation, respectively. $N^{j+1}(r,0)$ is isotope density vector at beginning of cycle (BOC) for the next core cycle. $N^j(r,\tau)$ vector is expressed as isotope density at ending of the cycle (EOC) in core cycle *j*. $N^j(r,\tau)$ is expressed as isotope density at BOC at core cycle *j*. S^j is a shifting matrix, with this matrix defined all loading and shifting of fuel in the core and defining the new fuel composition introduced into the core at BOC. An equilibrium core is achieved when it meets the following conditions:

$$N^{j+1}(r,t)=N^j(r,t) \qquad 0\le t\le \tau;$$

$$S^{j+1}=S^j \qquad \text{for all } j\text{; and}$$

$$N_{in}^{j+1}(r,0) = N_{in}^{j}(r,0) \qquad \text{for all } j \qquad (11)$$

By doing of calculations for eq. (8), (9), and (10) respectively through an iteration method taking into account the convergence values can be obtained an equilibrium core corresponding to the eq. (11).

Description of The RSG-GAS Core

Fuel plays an important role in the design of a reactor. RSG-GAS core uses a plate type with dimension 8.05 cm x 7.6 cm x 70 cm (the active core). RSG-GAS reactor core grid is 8.1 cm x 7.71 cm. For reactivity control, the control rods used in the reactor is fork-type, Ag-In-Cd material (80%, 15%, and 5 %) placed on the outside of the fuel control element [9]. The number of fuel plates in standard fuel elements (FE) and control (CE) of 21 plates and 15 plates, respectively. Table 1 presents the FE and CE geometry data used in the RSG-GAS reactor. Figures 1 and 2 show FE and CE with a fork-shaped absorber, used in this analysis.

Table 1. Geometry Data of RSG-GAS Fuel Assembly [9]

Geometry data	Value
Grid dimensions for standard fuel elements (FE) and control (CE), cm	7.71 x 81 x 60
Thickness of the fuel plate, cm	0.13
Cooling channel width, cm	0.255
Number of fuel plates in FE	21
Number of fuel plates in CE	15
Cladding material	AlMg2
Side plate material	AlMg1
Thickness of fuel cladding, cm	0.038
Dimension of active zone (*meat*), cm	0.054 x 6.275 x 60
Fuel material	U_3Si_2-Al
Fuel loading ^{235}U, g	250
Absorption material	Ag-In-Cd
Thickness of absorption, cm	0.338
Absorption cladding material	SS-321
Thickness of cladding absorpbtion, cm	0.085

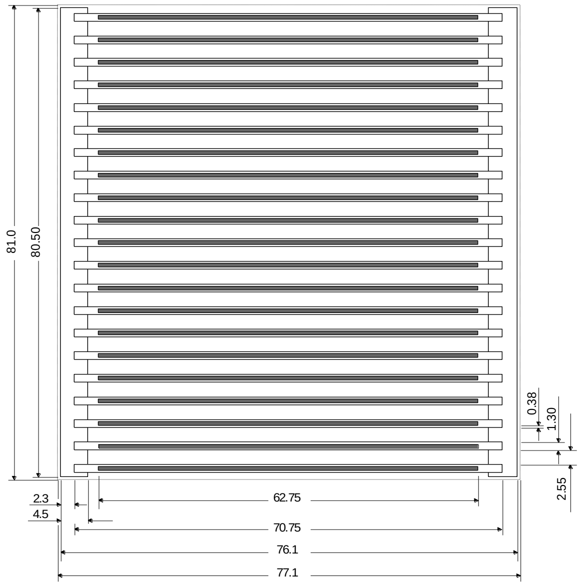

Figure 1. Standard Fuel Elements of the RSG-GAS Reactor [10]

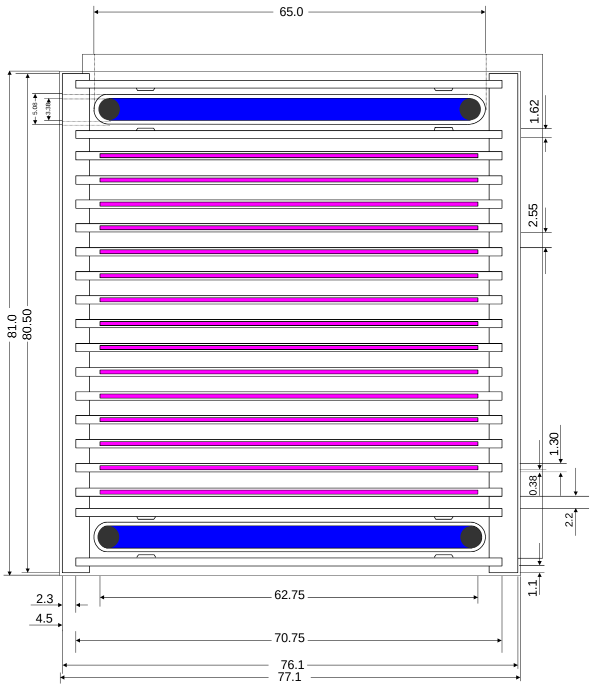

Figure 2. Control Rod Fuel Elements of the RSG-GAS Reactor [10]

II. RESEARCH METHOD

Core Design Limit

The RSG-GAS reactor is designed to operate at a nominal power of 30 MWth using 40 standard fuel elements (FEs) and 8 control fuel elements (CEs) in 10 x10 core lattices as shown in Figure 3. Two fork-type AgInCd that serves to control the population of neutrons inserted through the CE side.

RSG-GAS core using silicide fuels did not change the configuration of the core, thus the shield, the material of the core and the physical building are not changed from the design. The safety criteria and limitations used in the equilibrium core calculations are [12]:

a. Shut-down margin reactivity –0.5 %Δk/k.
b. Maximum radial power peaking factor (PPF) 1.4.
c. Maximum discharge burn-up 59%
d. The number and performance of all irradiation facilities within the core unchanged during the core conversion.

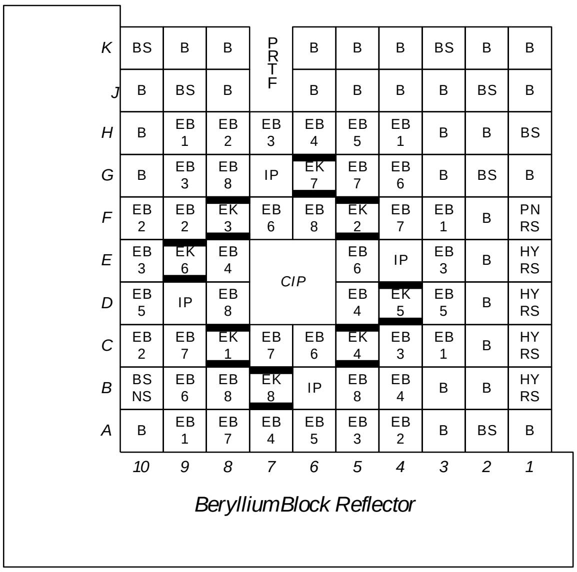

Figure 3. RSG-GAS Core Configuration (Numbers at EB and EK are Burn-Up Class) [11]

where: EB = Standard Fuel Element; EK = Standard Control Element; BE = Beryllium Reflector Element; BS = Beryllium Reflector Element with plug; IP = Irradiation Position; CIP = Center Position Irradiation; PNRS = Pneumatic Rabbit System; HYRS = Hydraulic Rabbit System.

Cell Calculation

RSG-GAS silicide fuel cell calculations were performed with the WIMSD-5B program package to generate the group constant of neutron diffusion in 4 groups of neutron energy. The neutron energy boundary requirements are used at 10 MeV, 0.821 MeV, 5.530 keV, 0.625 eV, and 0.0 eV [13]. Besides being a neutron energy function, the generated diffusion group constants are expressed in the fuel type function, the mass of ^{235}U, Xe conditions (without and equilibrium) and operating temperature (cold and hot).

Core Calculation

In the RSG-GAS core neutronic design, the calculated core parameters include reactivity equilibrium parameters, radial and axial power peaking factors, reactor control rods, kinetic parameters and neutron flux distribution in irradiation facilities. The reactivity equilibrium parameter was calculated to determine the adequacy of the core reactivity during the reactor operating in one cycle at 15 MWth. Besides that also, will be known the ability of shut-down reactivity of 8 control rods that exist in the core. Determination of the axial power peaking factor and reactivity of control rod were conducted by 3-dimensional neutron diffusion method, BATAN-3DIFF code. This is because the parameter depend on the position of control rod withdrawal [15]. The other core parameters were calculated by the neutron diffusion method, BATAN-FUEL 2-dimensional method.

III. RESULTS AND DISCUSSION

Macroscopic Cross-section of Fuel

The macroscopic cross-section results of the WIMSD-5B code are shown in Table 2. The macroscopic constant greatly depends on fuel mass loading and fuel burn-up. In the table the macroscopic constant value of uranium fuel with a mass loading of 250 gram used in the RSG-GAS core. The macroscopic constant is calculated by 4 groups of neutron energy used as input in the BATAN-2DIFF code for core calculation. Macroscopic constants are the diffusion constant (*D*), the sigma absorption (Σ_a), the sigma transport (Σ_t), and the sigma fission times the amount of neutron per fission release ($\upsilon\Sigma_f$). The larger the fuel burn-up fraction, the smaller the sigma fission, means that the consequences of the cycle length will be smaller. This macroscopic constant is very sensitive to the core calculation so it determines that the accuracy on the core calculation must be calculated properly and correctly. Macroscopic constants are calculated based on the function of the fuel burn-up that is from 0 up to 90%.

Table 2. Macroscopic Cross-Section for RSG-GAS Uranium Silicide Fuel

D_g	$\sum_a$	$\sum_t$	$\gamma\sum_f$	$\sum_{g\ to\ g'=1}$	$\sum_{g\ to\ g'=2}$	$\sum_{g\ to\ g'=3}$	$\sum_{g\ to\ g'=4}$
2.38E+00	9.59E-04	7.43E-02	1.33E-03	6.47E-02	7.39E-02	4.20E-04	1.61E-12
1.29E+00	6.00E-04	8.95E-02	6.90E-04	2.64E-21	1.69E-01	8.95E-02	9.69E-06
8.29E-01	1.31E-02	8.24E-02	1.07E-02	0.00E+00	2.47E-23	3.07E-01	8.24E-02
2.76E-01	8.77E-02	3.81E-04	1.52E-01	0.00E+00	0.00E+00	3.81E-04	1.12E+00
Burn-up = 0.1 %							
2.38E+00	9.59E-04	7.43E-02	1.33E-03	6.47E-02	7.39E-02	4.20E-04	1.61E-12
1.29E+00	6.00E-04	8.95E-02	6.89E-04	7.31E-13	1.69E-01	8.95E-02	9.69E-06
8.29E-01	1.31E-02	8.24E-02	1.07E-02	0.00E+00	2.43E-23	3.07E-01	8.24E-02
2.76E-01	8.77E-02	3.80E-04	1.52E-01	0.00E+00	0.00E+00	3.80E-04	1.12E+00
Burn-up = 47 %							
2.38E+00	8.76E-04	7.43E-02	1.11E-03	6.50E-02	7.39E-02	4.20E-04	1.71E-12
1.29E+00	4.65E-04	8.95E-02	3.92E-04	1.04E-10	1.69E-01	8.95E-02	9.69E-06
8.27E-01	1.27E-02	8.23E-02	6.17E-03	0.00E+00	1.29E-14	3.08E-01	8.23E-02
2.67E-01	6.55E-02	2.87E-04	9.78E-02	0.00E+00	0.00E+00	2.87E-04	1.18E+00
2.63E-01	5.76E-02	2.53E-04	7.95E-02	0.00E+00	0.00E+00	2.53E-04	1.21E+00
8.26E-01	1.24E-02	8.22E-02	3.26E-03	0.00E+00	5.34E-14	3.09E-01	8.22E-02
2.58E-01	4.76E-02	2.10E-04	5.61E-02	0.00E+00	0.00E+00	2.10E-04	1.24E+00
Burn-up = 90 %							
2.37E+00	7.92E-04	7.44E-02	8.88E-04	6.52E-02	7.40E-02	4.20E-04	2.04E-12
1.29E+00	3.32E-04	8.96E-02	1.00E-04	3.40E-10	1.69E-01	8.96E-02	9.70E-06
8.26E-01	1.21E-02	8.22E-02	1.60E-03	0.00E+00	6.01E-14	3.09E-01	8.22E-02
2.52E-01	3.58E-02	1.58E-04	2.92E-02	0.00E+00	0.00E+00	1.58E-04	1.29E+00

Burn-up Calculation Results

The result of the core calculation for fuel burn-up is calculated by using the Eq. [7] for each fuel on RSG-GAS core 90 which can be seen in Table 3. From the Table 3, it can be seen that the fuel burn-up fraction can be grouped in eight classes, i.e for the beginning of cycle (BOC), the average burn-up fraction is 0%, which expressed from sequence numbers 1 to 6 and 7.28% averaged from sequence numbers 7 to 12 and so on, to obtain other classes, the fuel burn-up fractions are 14.18%, 21.46%, 28.54%, 34.55%, 41.01%, and 46.99% respectively. The strategy of RSG-GAS fuel management is conducted with the 5/1 pattern which means the burn-up of 5 fuels 1 control rod are averaged. At the end of the cycle (EOC), the burn-up fuel classes are 7.30%, 14.24%, 21.61%, 28.49%, 34.55%, 40.96%, 46.88% and 52.62%. Five fuels and one control rod in the 8th class were replaced with a new one to form a new core, it is called the core 91. Five fuels and one control rod are transferred to the fuel storage pool to be cooled and treated as fuel waste. When the fuel is removed it is all visually checked for damage or defects. On the core 90, no fuel is damaged after the reactor operates 615 MWD at 15 MW average power. The maximum burn-up fraction was 56.72% in the 48th sequence number of RI-539 fuel, while the maximum safety requirement burn-up fraction limit was 59%. So it is still far from the limit of safety.

Table 3. Core Calculation Results for Fuel Burn-Up Core 90

Number	U (g)	Burn-up BOC (%)	Burn-up EOC (%)	Fuel code	Number	U (g)	Burn-up BOC (%)	Burn-up EOC (%)	Fuel code
1	248.02	0.00	7.05	RI-580	25	248.91	26.47	32.81	RI-553
2	248.69	0.00	6.84	RI-576	26	249.72	26.87	33.39	RI-552
3	247.37	0.00	7.31	RI-579	27	248.92	27.24	33.24	RI-555
4	248.53	0.00	8.49	RI-584	28	248.73	28.85	34.32	RI-554
5	248.38	0.00	7.55	RI-578	29	248.36	29.27	35.12	RI-556
6	248.76	0.00	6.57	RI-577	30	249.28	31.35	38.39	RI-552
7	250.21	6.56	13.11	RI-572	31	249.06	32.83	38.33	RI-548
8	250.37	6.82	14.72	RI-571	32	249.51	33.23	40.45	RI-550
9	249.01	7.04	14.65	RI-575	33	248.69	33.47	39.13	RI-547
10	250.21	7.27	14.26	RI-574	34	249.18	34.32	41.55	RI-549
11	249.83	7.53	14.06	RI-573	35	248.97	35.09	42.11	RI-551
12	248.53	8.48	16.62	RI-583	36	248.22	38.38	44.19	RI-543
13	249.38	13.04	20.16	RI-567	37	249.12	38.46	45.04	RI-561
14	249.64	13.97	21.30	RI-568	38	248.07	39.22	45.56	RI-542
15	250.08	14.16	21.15	RI-569	39	249.44	40.49	46.29	RI-545
16	250.12	14.52	21.59	RI-570	40	248.71	41.60	46.29	RI-544
17	248.62	14.69	21.04	RI-566	41	249.13	42.15	47.54	RI-546
18	248.35	14.69	24.43	RI-564	42	249.38	44.11	50.57	RI-534
19	249.38	20.04	26.61	RI-558	43	247.91	45.15	51.21	RI-540
20	248.99	20.88	27.05	RI-557	44	249.79	45.40	50.45	RI-533
21	248.73	21.06	27.39	RI-560	45	248.74	46.25	51.84	RI-535
22	249.30	21.19	28.97	RI-559	46	248.44	46.32	52.20	RI-536
23	248.86	21.52	29.39	RI-565	47	247.44	47.64	53.21	RI-541
24	248.84	24.27	31.58	RI-563	48	247.91	51.20	56.72	RI-539

The new core 91 was prepared. The fuel was rearranged according to the core configuration at the beginning of the cycle with 8 groups of fuel burn-up fractions inserted into the RSG-GAS reactor core. Fuel placement using fuel management calculations on RSG-GAS core requires precision and supervision so that there is no displacement. Based on the result of calculation using BATAN-FUEL code, the initial core configuration with 8 average burn-up classes of core 91 are 0%, 7.30%, 13.24%, 21.61%, 28.49%, 34.63%, 40.97%, and 46.99% with the fuel burn-up distribution shown in Table 4. The average burn-up at the end of the cycle for 8 classes of the fuel can be obtained 7.46%, 14.69%, 21.69%, 28.61%, 34.69%, 40.95%, 46.67, and 54.26% respectively, with a maximum fuel burn-up of 56.73% in sequence number of 48 with RI-540 fuel. The maximum fuel burn-up is still far below its safety limit. On a new core 91, 5 fuels and one control rod at the end of the cycle were replaced with a new one after operating 615 MWD at 15 MW average power. All fuel is not damaged after being checked visually and recorded back into the log book.

Table 4. Core Calculation Results for Fuel Burn-Up Core 91

Number	U (g)	Burn-up BOC (%)	Burn-up EOC (%)	Fuel code	Number	U (g)	Burn-up BOC (%)	Burn-up EOC (%)	Fuel code
1	248,01	0,00	6,57	RI-588	25	249,38	26,61	32,94	RI-558
2	248,26	0,00	6,86	RI-581	26	248,99	27,05	33,40	RI-552
3	248,03	0,00	7,05	RI-587	27	248,73	27,39	33,56	RI-560
4	248,32	0,00	8,49	RI-585	28	249,30	28,97	34,44	RI-559
5	247,55	0,00	7,31	RI-586	29	248,60	29,39	35,24	RI-565
6	248,17	0,00	8,49	RI-582	30	248,36	31,58	38,61	RI-563
7	248,76	6,57	13,64	RI-577	31	248,91	32,81	38,30	RI-553
8	248,69	6,84	14,09	RI-576	32	248,92	33,29	40,48	RI-555
9	248,02	7,05	14,33	RI-580	33	249,72	33,39	39,05	RI-552
10	247,37	7,31	14,67	RI-579	34	248,73	34,82	41,56	RI-554
11	248,38	7,55	14,76	RI-578	35	248,36	35,13	42,15	RI-556
12	248,53	8,49	16,64	RI-584	36	249,06	38,33	44,13	RI-548
13	250,21	13,11	20,21	RI-572	37	249,28	38,39	44,96	RI-562
14	249,83	14,06	21,05	RI-573	38	248,69	39,13	45,46	RI-547
15	250,21	14,26	21,24	RI-574	39	249,51	40,45	46,27	RI-550
16	249,01	14,65	21,39	RI-575	40	249,18	41,55	46,24	RI-549
17	250,37	14,72	21,73	RI-571	41	248,97	42,12	46,51	RI-551
18	248,53	14,62	24,53	RI-583	42	248,22	44,19	50,61	RI-543
19	249,38	20,16	26,73	RI-567	43	249,12	45,04	51,11	RI-561
20	248,62	21,04	27,22	RI-566	44	248,07	45,56	50,61	RI-542
21	250,08	21,15	27,46	RI-569	45	249,44	46,29	52,17	RI-545
22	249,64	21,30	29,04	RI-568	46	248,71	46,29	51,88	RI-544
23	250,12	21,59	29,44	RI-570	47	249,13	47,54	53,09	RI-546
24	248,35	24,43	31,74	RI-564	48	247,91	51,22	56,73	RI-540

Table 5 is the result of calculation for fuel burn-up of core 92 which is distributed to 8 classes. At the beginning cycle, at the core 92 obtained the average fuel burn-up for the 8 classes were 0%, 7.31%, 14.61%, 21.64%, 28.61%, 34.65%, 40.99%, and 46.92% respectively. As for the end of the cycle, the average fuel burn-up for 8 classes were 7.04%, 14.34%, 21.48%, 28.42%, 34.56%, 40.81%, 46.65%, and 52.46%, respectively. The maximum burn-up is 56.42% at the sequence number of 48 for RI-561 fuel. The fuel has maximum burn-up still far from the established safety limits. At the end of cycle, 5 fuels and one control rod at class 8 of burn-up are issued for the largest burn-up. Fuels with distributed fuel burn-up fractions for each class of each fuel can be seen in Table 5. The results of this analysis shows that at the energy operation of 615 MWD with a power level of 15 MW does not exceeded its safety limits of maximum burn-up.

Table 5. Core Calculation Results for Fuel Burn-Up Core 92

Number	U (g)	Burn-up BOC (%)	Burn-up EOC (%)	Fuel code	Number	U (g)	Burn-up BOC (%)	Burn up EOC (%)	Fuel code
1	247.40	0.00	6.79	RI-594	25	249.38	26.73	32.81	RI-567
2	247.53	0.00	6.61	RI-589	26	248.62	27.22	33.48	RI-566
3	248.04	0.00	7.04	RI-593	27	250.08	27.46	33.21	RI-569
4	247.81	0.00	8.18	RI-591	28	249.30	29.08	34.33	RI-568
5	247.57	0.00	7.27	RI-592	29	250.12	29.44	35.05	RI-570
6	247.66	0.00	6.34	RI-590	30	248.35	31.74	38.50	RI-564
7	248.17	6.57	12.92	RI-582	31	249.38	32.94	38.22	RI-558
8	248.26	6.88	14.49	RI-581	32	248.73	33.40	40.35	RI-560
9	248.01	7.05	14.38	RI-588	33	248.99	33.56	39.01	RI-557
10	248.03	7.31	14.06	RI-587	34	249.30	34.44	41.39	RI-559
11	247.55	7.56	13.87	RI-586	35	248.86	35.24	41.99	RI-565
12	248.32	8.49	16.33	RI-585	36	248.91	38.30	43.89	RI-553
13	248.76	13.15	20.00	RI-577	37	248.38	38.61	44.93	RI-563
14	248.38	14.09	21.17	RI-578	38	249.72	39.05	45.14	RI-552
15	247.37	14.33	21.08	RI-579	39	249.51	40.48	46.06	RI-555
16	248.02	14.67	21.49	RI-580	40	248.73	41.56	46.08	RI-554
17	248.69	14.76	20.88	RI-576	41	248.36	42.15	47.34	RI-556
18	248.53	16.64	24.25	RI-584	42	249.06	44.13	50.35	RI-548
19	249.38	20.21	26.52	RI-572	43	249.28	44.96	51.11	RI-562
20	250.37	21.05	26.99	RI-571	44	248.69	45.46	50.80	RI-547
21	250.21	21.24	27.31	RI-574	45	249.18	46.24	51.62	RI-549
22	249.83	21.39	28.86	RI-573	46	248.71	46.26	51.92	RI-550
23	249.01	21.73	29.29	RI-575	47	248.97	47.51	52.86	RI-551
24	248.53	24.53	31.56	RI-583	48	249.12	51.11	56.42	RI-561

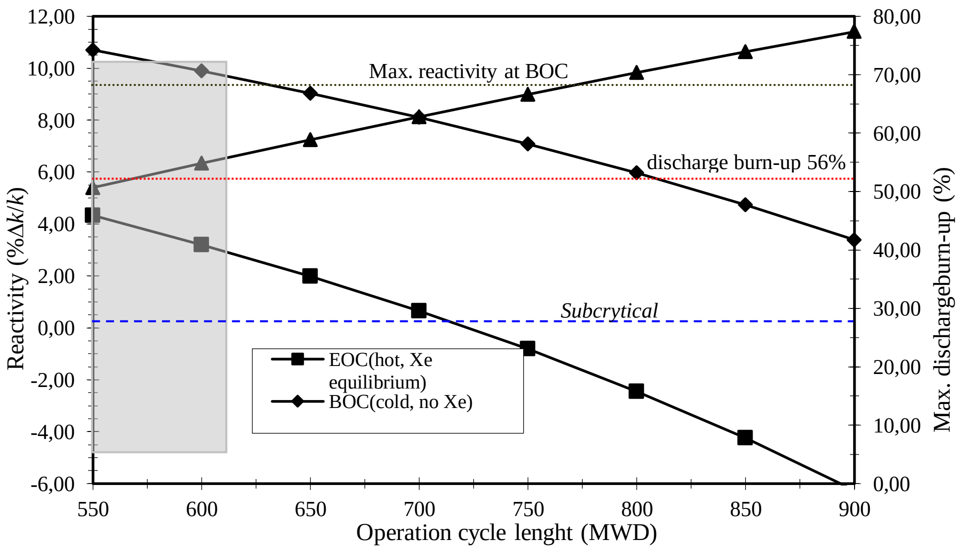

Figure 4. Excess Core Reactivity and Fuel Burn-Up as Function of Cycle Length

Equilibrium Core

Figure 4 shows the reactivity value and maximum fuel burn-up as a function of operation cycle length for silicide c equilibrium ore with a fuel density of 2.96 gU/cm^3. The calculation results show that the length of the cycle that meets the design limit is between 525-620 MWD.

Table 6. Nutronic Parameter of Core 92

Core parameter	Silicide fuel 2.96 gU/cm
Cycle length (MWD/days)	614.6/20.48
Average burn-up at BOC (%)	23.8
Average burn-up at EOC (%)	30.3
Average discharge burnup (%)	52.3
Max discharge burn-up (%)	56.0
Max radial PPF	1.23
Reactivity balance (% $\Delta k/k$):	
- hot to cold	0.62
- Xenon equilibrium	3.66
- burn-up for one cycle	2.51
- experiment. partial Xenon override	2.97
- core excess reactivity	9.76
- control rod reactivity worth N	-13.60
- shutdown margiun reactivity	-1.10
Kinetic parameter:	
Delayed neutron fraction. (β_{eff})	7.186×10^{-3}
Neutron generation time(Λ.μs)	58.2830
Prompt neutron life time (l. s)	64.513
Prompt neutron decay constant (α.s^{-1})	111.394

Table 6 shows the neutronic parameters of RSG-GAS reactor equilibrium core. These parameters are calculated using BATAN-EQUIL code. After optimization, the length of the core operating cycle of silicide fuel is 614.6 MWD. This is obtained by finding the length of the cycle resulting in a maximum discharge burn-up at EOC of 56%. The core calculations performed using the BATAN-EQUIL code resulted in a composition of the core burn-up for the equilibrium core configuration. The burn-up fuel data is used in all core calculations for the beginning and end of the cycle and also the calculation of the control rod reactivity worth. At the end of cycle, core reactivity at equilibrium xenon conditions is calculated by incorporating core burn-up values for one cycle. The value of the core reactivity (ρ) at EOC and the maximum radial power peaking factor (PPF) value are shown in Table 6. The minimum shut-down margin is effective to shut the reactor down at the end of the cycle also qualifies for the stuck rod condition because it is less than - 0.5% $\Delta k/k$ so that the reactor can be operated safely. The maximum peak power factor value generated for each core is also eligible, as it is less than the 1.4 limit requirement.

IV. CONCLUSION

Based on the analysis of RSG-GAS core fuel management in the calculation of the fuel burn-up fraction using the BATAN-FUEL code on silicide fuels with 2.96 gU/cm^3 density, loading and shifting patterns of fuels used can be applied to the entire equilibrium core. All the equilibrium core parameters meet the safety criteria and irradiation facility performance has not changed. The safety margin of the maximum fuel burn-up fraction does not exceed 59% limit so that from all three operated cores, they all meet the requirements of periodic safety review which become the permit terms of the subsequent reactor operating license.

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