Annals of Nuclear Energy 98 (2016) 211–217

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Fuel element burnup measurements for the equilibrium LEU silicide RSG GAS (MPR-30) core under a new fuel management strategy

Surian Pinem [a], Peng Hong Liem [b,*], Tagor Malem Sembiring [a], Tukiran Surbakti [a]

[a] Center for Nuclear Reactor Technology and Safety, Indonesian National Nuclear Energy Agency (BATAN), Puspiptek Complex, Serpong, Tangerang Selatan 15314, Indonesia
[b] Nippon Advanced Information Service (NAIS Co., Inc.), 416 Muramatsu, Tokai-mura, Naka-gun, Ibaraki 319-1112, Japan

ARTICLE INFO

Article history:
Received 7 June 2016
Received in revised form 5 August 2016
Accepted 11 August 2016
Available online 19 August 2016

Keywords:
Burnup measurement
Equilibrium core
LEU silicide fuel
RSG GAS
Subcritical

ABSTRACT

After the equilibrium LEU silicide core of RSG GAS was achieved, there was a strong need to validate the new fuel management strategy by measuring burnup of fuel elements comprising the core. Since the regulatory body had a great concern on the safety limit of the silicide fuel element burnup, amongst the 35 burnt fuel elements we selected 22 fuel elements with high burnup classes i.e. from 20 to 53% loss of U-235 (declared values) for the present measurements. The burnup measurement method was based on a linear relationship between reactivity and burnup where the measurements were conducted under subcritical conditions using two fission counters of the reactor startup channel. The measurement results were compared with the declared burnup evaluated by an in-house in-core fuel management code, BATAN-FUEL. A good agreement between the measured burnup values and the calculated ones was found within 8% uncertainties. Possible major sources of differences were identified, i.e. large statistical errors (i.e. low fission counters' count rates), variation of initial U-235 loading per fuel element and accuracy of control rod indicators. The measured burnup of the 22 fuel elements provided the confirmation of the core burnup distribution planned for the equilibrium LEU silicide core under the new fuel management strategy.

1. Introduction

Reaktor Serba Guna G.A. Siwabessy (RSG GAS; previous name MPR-30) is a Be-reflected, light-water-moderated and -cooled, 30 MWth (max.) multipurpose pool-type reactor which was commissioned in 1987. The reactor main data are shown in Table 1 (Batan, 1987). Originally, the core used material testing reactor (MTR) type low enriched uranium (LEU; 19.75 w/o U-235 enrichment) oxide fuel elements (FEs). On the 10 × 10 core grid positions there are 40 standard FEs (each consisting of 21 fuel plates as depicted in Fig. 1), 8 control elements (CEs, each consisting of 15 fuel plates as depicted in Fig. 2) initially loaded with 250 and 178.6 g U-235 respectively, Be reflector elements, and other irradiation facilities. This fuel loading corresponds to a uranium meat density of 2.96 g U/cm^3. The original nominal core cycle is 25 days or equivalent to 750 MWD per cycle. The equilibrium core is divided into seven burn-up classes with an average burn-up step of approximately 8% loss of U-235.

At the end of 90's, the core conversion program from oxide to silicide fuels with higher U-235 loading per FE was initiated to optimize the reactor utilization. The optimized equilibrium silicide core with a new fuel management strategy for U-235 loading up to 350 g U-235/FE (equivalent to a uranium meat density of 4.15 g U/cm^3) were found (Liem et al., 1998). Under the new fuel management strategy, the silicide core requires 5 new FEs and one new CE at the beginning of cycle (BOC) while the original oxide core requires 6 new FEs and 1 or 2 CEs. A more important benefit of the new fuel management strategy is the regularity of FE and CE loading, discharging and shuffling pattern from end of cycle (EOC) to BOC of the next core cycle (Liem et al., 1998, cf. Table 2). The new fuel management strategy allows a shorter outage time between core cycles since the operators do not need to seek for an optimal core configuration for each cycle. On top of that, the human error in loading and shuffling the FEs and CEs is minimized since the pattern is fixed. The transition core design to reach gradually such equilibrium cores have been also established (Liem and Sembiring, 2010). At present, the original oxide core has been completely converted into new silicide cores using the same uranium fuel loading (250 g U-235/FE) under the new fuel management strategy. The present equilibrium silicide core and reflector configuration is shown in Fig. 3. In the figure, the index 1–8 denotes the burnup class where 1 is for fresh fuel and 8 is the most burnt fuel.

* Corresponding author.
E-mail address: liemph@nais.ne.jp (P.H. Liem).

http://dx.doi.org/10.1016/j.anucene.2016.08.010
0306-4549/

Table 1
Reactor main design data of RSG GAS (present silicide core).

General	
Reactor Type	Pool Type
Fuel Element Type	LEU Silicide MTR
Cooling System	Forced Convection Down Flow
Moderator/Coolant	H_2O
Reflector	Be & H_2O
Nominal Power (MWt)	30
Core Characteristics	
No. of Fuel Elements	40
No. of Control Elements	8
No. of Fork Type Absorber (pairs)	8
Nominal Cycle Length (fpd)	25
Ave. Burn-up at BOC (% loss of U-235)	23.3
Ave. Burn-up at EOC (% loss of U-235)	31.3
Ave. Discharge Burn-up at EOC (% loss of U-235)	53.7
Fuel/Control Elements	
Fuel/Control Element Dimension (mm)	$77.1 \times 81 \times 600$
Fuel Plate Thickness (mm)	1.3
Coolant Channel Width (mm)	2.55
No. of Plate per Fuel Element	21
No. of Plate per Control Element	15
Fuel Plate Clad Material	$AlMg_2$
Fuel Plate Clad Thickness (mm)	0.38
Fuel Meat Dimension (mm)	$0.54 \times 62.75 \times 600$
Fuel Meat Material	U_3Si_2Al
U-235 Enrichment (w/o)	19.75
Uranium Density in Meat (g/cm^3)	2.96
U-235 Loading per Fuel Element (g)	250
U-235 Loading per Control Element (g)	178.6
Absorber Meat Material	Ag–In–Cd
Absorber Thickness (mm)	3.38
Absorber Clad Material	SUS-321
Absorber Clad Thickness	0.85

After the new equilibrium silicide cores have been achieved there is a strong need to validate the new silicide fuel management strategy by measuring burnup of FEs comprising the core (IAEA, 1992). Burnup measurements either by a non-destructive method (Liem et al., 2013) or by a destructive method (Ginting and Liem, 2015) as we have conducted for a particular FE and fuel plates are not suitable for the present objective since we plan to measure many FEs. Instead, we use a burnup measurement method based on a linear relation between reactivity and burnup where the measurements are conducted under a subcritical condition. Even using the method, burnup measurements covering numerous FEs would demand a long outage period of the reactor which might disturb the planned target irradiation and neutron beam tube utilization. In addition, since our regulatory body has a great concern on the safety limit of the silicide FE burnup (approximately 60% loss of U-235) we select FEs with high burnup classes for the present work. The measurement results will be compared with the estimated burnup evaluated by an in-house, in-core fuel management code, BATAN-FUEL (Liem, 1996).

The paper is organized as the following. In Section 2, the burnup measurement method and experimental procedure are explained. Section 3 discusses measurement results and comparison with the calculation results. The last section, Section 4, provides the concluding remarks of the present work.

2. Burnup measurement under subcritical condition

2.1. Measurement method

There are various methods widely known and available for burnup measurement of FEs in research reactors (IAEA, 1992) and some of them are also used in power reactors. These methods can be divided into non-destructive and destructive ones, as in the post irradiation examination (PIE) activity we have conducted for a particular silicide FE and fuel plates of RSG GAS (Liem et al., 2013; Ginting and Liem, 2015). The destructive methods will not be discussed further since they are not practical for the present work's objective. As for the non-destructive methods, most commonly used methods of determining research reactor fuel burnup are (1) reactor physics calculations, (2) measurement of reactivity effects, and (3) gamma-ray spectrometry (IAEA, 1992). In our research and development activity for manufacturing, irradiating and testing (PIE) high loading silicide fuel elements for RSG GAS, we adopted the gamma-ray spectrometry for fuel burnup measurement (Liem et al., 2013). The measured Cs-134/Cs-137 activity ratio distributions were used to estimate the FE averaged burnup. Along with the gamma-ray spectrometry method, we also used reactor physics calculations to verify the measured burnup values. However, not limited to our case, the gamma-ray spectrometry method requires the FE to be transferred to a hot cell for the measurements. If the FE is still used for the next core cycle operation and/or if the number of FE to be measured is big then the gamma-ray spectrometry method seems not practical.

Fuel burnup measurement methods based on the reactivity effects require much shorter measurement time and there is no need to transfer FEs to a hot cell. These methods can be divided further based on whether the measurements are done under critical or subcritical conditions. A fuel burnup measurement method under subcritical condition proposed by Binh et al. (1997) is adopted for the present work since the time require for the measurements is short (i.e. the reactor need not be brought to a critical condition each time an FE is measured). The method assumes a linear relationship between FE reactivity and its burnup. We have checked that the burnup of FEs to be measured does not exceed 53% loss of U-235 and the linear relationship assumption is acceptable. The reactivity and neutron density relation for a subcritical system is straightforward (for example, see Keepin, 1965) and for the detail readers are suggested to refer to the publication by Binh et al. (1997). Here we only show the main results as follows.

The relationship between the reactivity of a fresh FE (ρ_0) and the reactivity of the *i-th* FE (ρ_i) to be measured can be written as the following.

$$\begin{aligned} \rho_i &= c_i \rho_0 \\ c_i &= \frac{N_0}{N_0 - N_{bd}} \times \frac{N_i - N_{bd}}{N_i} \\ i &= 1, 2, \ldots, G \end{aligned} \tag{1}$$

Here, N_0, N_i and N_{bd} are the neutron density when the fresh FE, the *i-th* FE and no FE is inserted into a certain location in the core under a subcritical condition, respectively. G is the number of FE to be measured for the same and fixed core configuration and control rod bank position (hereafter it is called a sequence).

If the assumption of the linear burnup reactivity is valid then one can express:

$$\rho = a + b \times BU \tag{2}$$

where a and b are coefficients; BU and ρ are the FE burnup and reactivity, respectively. When the reactivities are measured in the same core configuration and control rod bank position, i.e. in a sequence, then by using Eqs. (1) and (2), the *i-th* FE burnup is

$$BU_i = \rho_0 (c_i - 1)/b \tag{3}$$

Consequently, the relative burnup of the *i-th FE*, BU_i^*, in comparison with the G measured fuel elements, is: