Nuclear Engineering and Design 267 (2014) 172–179

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Prototype studies on the nondestructive online burnup determination for the modular pebble bed reactors

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HIGHLIGHTS

- Prototype study of online burnup measurement for HTR proves its feasibility.
- Calibration and its correction of burnup assay device is discussed and verified.
- Analysis of simulated gamma spectra shows good performance of spectra-unfolding method.

ARTICLE INFO

Article history:
Received 11 March 2013
Received in revised form
30 November 2013
Accepted 2 December 2013

PACS:
25.85.Ec
28.41.Bm
28.41.Rc
29.40.Wk

ABSTRACT

The online fuel pebble burnup determination in future modular pebble bed reactor is implemented by measuring nondestructively the activity of the monitoring nuclide Cs-137 with HPGe detector on a pebble-by-pebble basis. Based on a full size prototype the feasibility is investigated. The prototype was first tested by using double sources to show that a precision of 2.8% (1σ) can be achieved in the determination of the Cs-137 net counting rate. Then, the relationship between the Cs-137 activity and the net counting rate recorded in the HPGe detector is calibrated with a standard Cs-137 source contained in the center of a graphite sphere with the same dimension as a real fuel pebble. Because the self attenuation of the calibration source differs with a fuel pebble, a correction factor of 1.07 ± 0.02 ($p = 0.95$) to the calibration is derived by using the efficiency transfer method. Last, by analyzing the spectra generated with KORIGEN software followed by Monte Carlo simulation, it is predicted that the relative standard deviation of the Cs-137 net counting rate can be still controlled below 3.5% despite of the presence of all the interfering peaks. The results demonstrate the feasibility of utilizing HPGe gamma spectrometry in the online determination of the pebble burnup in future modular pebble bed reactors.

1. Introduction

The high temperature gas cooling reactor (HTGR) is drawing great attention because of its intrinsic safety (IAEA-TECDOC-1674, 2012; Hawari and Chen, 2002; Su et al., 2006). In the type of the modular pebble bed reactor (MPBR), the fuel balls undergo fast multi-circulation during the running of the reactor. The pebble flow controlling system sends a circulation/discharge command on a pebble-by-pebble basis according to the individual burnup, which is online assessed nondestructively via the activity of a certain monitoring nuclide (Matsson and Grapengiessen, 1997; Terremoto et al., 2000; Ansari et al., 2007; Willman et al., 2006). It has been proposed widely that Cs-137 can be used as the burnup monitoring nuclide because the single pebble activity of Cs-137 depends monotonously on the burnup with rather resistance against the variation of neutron flux or irradiation history (Zhang et al., 2008; Hawari and Chen, 2005; Chen et al., 2003; Zhang and Shang, 2009).

When the power of the pebble bed reactor is raised, the circulation rate of the pebbles increases dramatically and leaves very short time (referenced as cooling time) for the radioactive nuclides in the fuel pebble to decay before online measurement is performed. For the reactor under design, the typical cooling time is 50 h. Due to the feature of fast pebble circulation on MPBR, the radiation background contains a large mount of peaks contributed by the fission products which are not decayed out during the short cooling time. Particularly, in the vicinity of the Cs-137 662 keV peak, intense peaks of Nb-97 (657.9 keV), Ce-143 (664.6 keV) and I-132 (667.6 keV) are presented. To discriminate the Cs-137 peak from the intense interfering peaks, it is proposed to utilize the high purification Germanium (HPGe) detector for its powerful peak identification.

Fig. 1 shows a schematic diagram of the burnup measurement system. The fuel balls are moving slowly down in the reactor core

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http://dx.doi.org/10.1016/j.nucengdes.2013.12.036

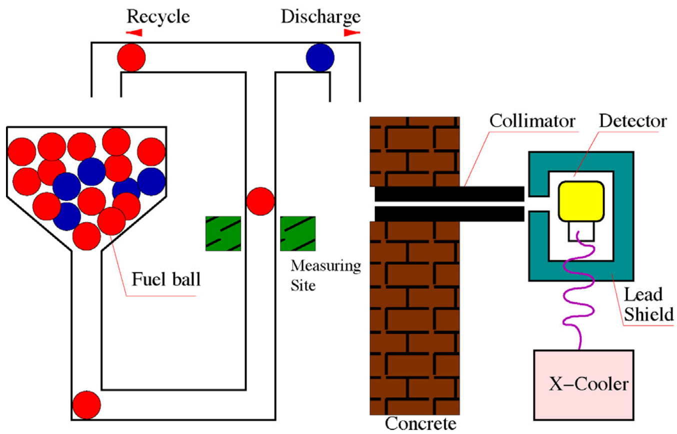

Fig. 1. Schematic view of the burnup measurement system. At the measuring site, the fuel ball is stored in a steel container. The HPGe crystal is placed vertically to gain a slightly higher efficiency.

to generate fission energy with an average flow rate of six thousand pebbles/day. Due to the random feature of the movement in history, the burnup of an individual ball cannot be evaluated in advance by conventional calculation. Thus, an online assessment of the burnup is required to determined whether the ball shall be recycled to the core or be discharged to a waste storage. Since the activity of Cs-137 is adopted to tag the burnup, it is of importance to achieve the nominated precision of determining the Cs-137 activity, upon which the pebble flow controlling system makes a circulation/discharge judgment to each individual pebble. In order to quantitatively study the feasibility of the online pebble burnup measurement, in this paper the design and test of a full size prototype of the burnup measuring system based on the KORIGEN simulations (Matsson, 1995; Fischer and Wiese, 1983) with certain reactor power and irradiation history is performed. The achievable precision at percent level has been demonstrated for determining experimentally the Cs-137 counting rate in high background using two standard sources. The calibration scheme of the system efficiency is proposed and tested in comparison to the Monte Carlo simulation. The correction factor of the efficiency attributed to the different self attenuation is derived by using the efficiency transfer method. Furthermore, the analysis are extended to the KORIGEN generated gamma spectra with complicated radiation background. The paper is structured as following. Section 2 is the KORIGEN calculation of the single pebble radioactivity and the design of the prototype. Section 3 presents the experimental results with standard source in comparison with Monte Carlo simulation. In Section 4 the analysis is extended to the complicated gamma spectra predicted with KORIGEN and Monte Carlo simulations. Section 5 is the summary.

2. KORIGEN simulation and the design of the prototype

The total gamma activity of a single fuel pebble is an essential factor in the design of the burnup measurement. It depends mainly on the burning history which includes the burnup and the neutron flux. Since there is no existing pebble reactor running so far, as the first step, it is suggested to employ KORIGEN software developed by German KfK nuclear research center (Matsson, 1995; Fischer and Wiese, 1983) to compute the radioactivity of the fuel pebble with given burnup under different neutron flux. In addition to the neutron spectrum, the fuel mass and the enrichment of the Uranium are all required by the software as input. In our calculation, the fuel mass is set to 7 g and two Uranium enrichments, 8.5% (I) and 4.2% (II) which corresponds to an initial reactor and an equilibrium reactor, respectively, are used. Due to the scattering and absorption effect, a fuel pebble passing through different part of the core experiences

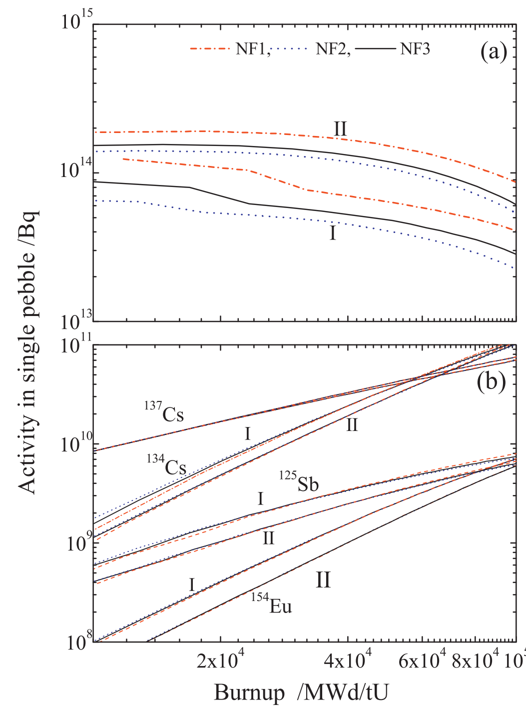

Fig. 2. Total activity (a) and activities of selected isotopes (b) in a single pebble as a function of burnup for pebbles at different neutron exposures NF1 (dish-dotted), NF2 (dashed) and NF3 (solid), respectively.

different neutron flux. Generally speaking, the pebbles in the center of the reactor core experiences higher neutron flux than those near the edge of the core. To see further the effect of the neutron flux, three simplified scenarios are considered in the calculation. (1) The pebble is flowing down in the center of the reactor core, corresponding to the maximum neutron flux (dubbed as NF1); (2) the pebble is flowing down along the inner wall of the reactor core, corresponding to the minimum neutron flux (NF2) and (3) the pebble is flowing down between the wall and the center, corresponding to the average neutron flux (NF3). Fig. 2(a) shows the total activity of a single pebble as a function of burnup for pebbles with less enriched fuel (I) and more enriched fuel (II), respectively. In a wide range of burnup above about 10,000 MWd/tU, the total radiation of the pebble decreases with the burnup, showing significant dependence on the fuel enrichment and the neutron fluxes that the pebble has been experienced. This is due to the competition between the short lived radioactive products and the long lived products. The activity of the short lived nuclides, which decay quickly, is approximately proportional to the current power P expressed by $P = f_n \sigma N E$, where f_n is the neutron flux, N is the number of fuel atoms, E is the energy released in each fission event and σ is the cross section. It is clear from this expression that the neutron flux has a direct influence to the production and that the activities of the short lived nuclides mainly depend on the leftover of the fuel (related to N) which naturally decreases with the burnup. While for the long lived nuclide, the activities depends mainly on the amount of the depleted fuel which is translated to the burnup if neglecting the side feed effect and the decay lose. Fig. 2(b) presents the single pebble activity of various selected isotopes of long life in the mass region of Uranium fission as a function of burnup. Interestingly, despite of the decreasing trend of the total activity, the single pebble activities of the selected isotopes exhibit a monotonous increasing trend with burnup, showing a slighter dependence on the neutron flux or the core history. Particularly the activity of Cs-137 is almost independent on the history because there is rare side feed to Cs-137 from the secondary decay of the surrounding nuclides. Therefore, even