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Feasibility studies on the burnup measurement of fuel pebbles with HPGe gamma spectrometer

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ABSTRACT

The feasibility of utilizing a High Purity Germanium (HPGe) detector for the fuel element burnup measurement in a future Modular Pebble Bed Reactor (MPBR) was studied. First, the HPGe spectrometer was set-up for running the detector at high count rates while keeping the energy resolution adequately high to discriminate the Cs-137 peak from other interfering peaks. Based on these settings, the geometrical conditions are settled. Next, experiments were performed with Co-60 and Cs-137 sources to mimic the counting rates in real applications. With the aid of KORIGEN and MCNP/G4 simulations, it was demonstrated that the uncertainty of the Cs-137 counting rate can be well controlled within 3.5%. Finally, a full size prototype was tested in comparison with detailed Monte Carlo simulation and the efficiency transfer method was further utilized for efficiency calibration. To reduce the uncertainty in the efficiency transfer process, a standard point source embedded in a graphite sphere was used for efficiency calibration. The correction factor due to pebble self-attenuation was carefully studied.

1. Introduction

The fuel balls undergo a multipass cycle in the Modular Pebble Bed Reactors (MBPR). Because of the serious inaccuracy of the computational method, which is conventional for performing the in-core fuel management in the existing water reactors, a non-destructive determination of the burnup is desired to provide the distributed control system with an online circulation/discharge judgment on a pebble-by-pebble basis in some bed-like reactors [1,2]. In various reactor applications, gamma ray spectrometry has been proposed as an effective non-destructive method for burnup determination [3–11] as well as the spatial irradiation distribution [12,13] by measuring the activity (activity ratio) of given monitor nuclide(s). Among all kinds of fission products, Cs-137 has been proposed to be one of the effective burnup indicators for its long life time and the clear correspondence to the burnup of the fuel pebble with rather resistance to the power history [14,15].

Nevertheless, characterized by very short cooling time, the fission of the fissile materials in MBPR produces various radionuclides that emit large amount of gamma rays over the whole energy spectrum, and hence, as shown by various simulation results [1,16–18] and some testing results, the Cs-137 full energy peak (FEP) is likely to be obscured by the neighboring gamma rays in short cooling time. For instance, in almost all stages of the burnup, the 658 keV peak from Nb-97 is presented [17]. Thus, in order to identify the 662 keV Cs-137 peak, energy resolution better than 2 keV is highly desired. In this aim, High Purity Germanium (HPGe) gamma detectors have been widely proposed.

Two important aspects have to be considered in the design of the burnup measurement system for MPBR:

(i) Due to very short cooling time, the cycling fuel element with a certain burnup has very high gamma radioactivity contributed by all kinds of fission products. If one lower the radiation level and hence the dead time by applying a sharp geometrical collimator, the FEP counts of the labeling Cs-137 are also suppressed and a larger statistical error is expected. On the other hand, to increase the throughput rate of the spectrometer by applying a fast setting of the HPGe electronics, the performance degrades. Therefore, for the MPBR under design, it is of extreme importance to optimize the working parameters, including the shaping time, geometrical collimation and shielding. This allows to have the activity determination with minimal uncertainty within a typical counting time of some tens of seconds after a cooling time lasting typically tens of hours.

(ii) Unless a real fuel ball with well defined Cs-137 activity is used as calibration source, the self-attenuation of the fuel ball is essential and has to be corrected or calibrated in the determination of the Cs-137 activity from the net counting rate of Cs-137 obtained by the HPGe. Suitable corrections have to take into account differences in attenuation and self-attenuation.

In this paper, the main results of the experimental conditioning of an HPGe gamma spectrometer for fuel pebbles burnup

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measurements are presented. Following the efficiency transfer approach [19], efficiency calibration was carried out based on a Cs-137 point source embedded in a graphite ball. The self-attenuation factor correction was carefully evaluated. The paper is arranged as following. Section 2 presents briefly the principle of measuring the fuel ball burnup. In Section 3, the experimental settings of the HPGe detector is investigated, leading to the studies on the precision of determining the net counting rate of Cs-137 gamma emission. In Section 4, the method to measure the Cs-137 activity of a fuel ball with self-attenuation correction is studied. Section 5 is the summary.

2. Method of measuring the burnup of the fuel ball

Fig. 1 shows the sketch of a burnup measuring system on a pebble bed reactor. Each fuel ball undergoes a multipass cycle. Before a certain ball is discharged from or refueled to the reactor, the gamma activity of the indicator nuclide, namely Cs-137, is nondestructively measured by an HPGe gamma ray spectrometer placed a few meters to the source with a concrete shielding and collimator in between. The average measuring time for each circular ball is about 20 s. Typically, the cooling time since the ball leaves the core to the measuring position is about 2 days. With the 662 keV FEP net counting rate n recorded by the spectrometer, the Cs-137 activity A is then derived by

$$A = n/\eta = n\frac{A_0}{n_0} \tag{1}$$

where η is the FEP efficiency of the system. Since the value of η depends on many effects, which include the self-attenuation of the fuel ball, the geometry filtering factor, the attenuation on the whole flying path and the efficiency of the detector, and is thus not straightforward to be predetermined accurately. With Monte Carlo simulation or empirical approach, the FEP efficiency can be determined with rather high accuracy if all detector related parameters are provided [20,21]. Alternatively, it is nature to adopt a calibration source with well defined activity A_0 and material composition identical to the fuel ball to calibrate η under identical geometrical conditions. The FEP efficiency η is then written as A_0/n_0, with the net counting rate of the calibrating source n_0 being predetermined off-line with high precision. It is shown from formulae (1) that the accuracy of the activity A is then mainly determined by the online measurement precision of n.

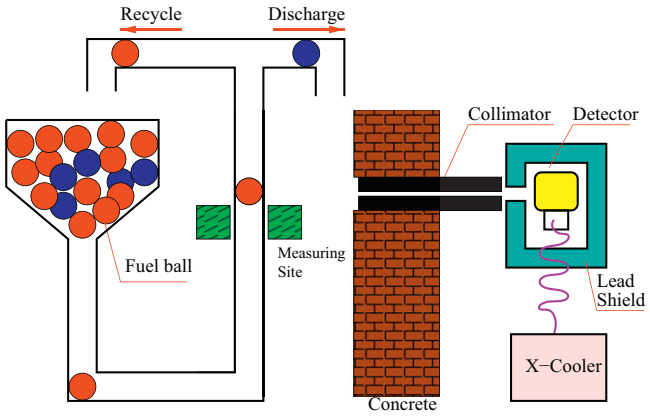

Fig. 1. Sketch of the burnup measuring system. At the measuring site, the fuel ball is stopped in a steel container. The tungsten collimator of 540 mm is embedded in a thick concrete wall. The distance between the source and the detector is about 4.9 m. The HPGe crystal is placed vertically to gain a slightly higher efficiency.

Practically, however, a fuel ball with well-defined activity is usually unavailable. Alternatively, we applied a well-defined point source for efficiency calibration. As a consequence, the self-attenuation of the point source differs from a fuel ball and correction has to be taken into account. Thus the accuracy of the self-attenuation correction factor is essential in the determination of η in formulae (1).

3. Precision of determining the net counting rate *n*

With a given measuring time, it is supposed to run the HPGe spectrometer at maximum throughput rate for the highest statistics. On the other hand, the energy resolution shall be adequately high for the discrimination of Cs-137 peak from interfering peaks generated by the residual radiation of the fission products with intermediate half-life. Since the performance of the energy resolution and throughput rate depends differently on the running parameters of the spectrometer, the optimization of the HPGe settings is first studied. Then the precision of the net counting rate of Cs-137 is evaluated.

3.1. Settings of the HPGe detector

The whole spectrometer consists of an HPGe gamma detector, an electrical cooling device (X-Cooler II) and a suitable fast electronics (DSPEC+) from ORTEC. The cylindric p-type HPGe crystal is 43.3 mm in height and 62.6 mm in diameter, with a ϕ10.8 mm × 30 mm hollow copper electrical pole fed in the axial center. The relative efficiency of the HPGe detector is about 30% and the working high voltage +2300 V. The preamplifier adopts the optical feed back technique to avoid saturation of the spectrometer at high incident rate.

For the conditioning, two gamma sources are used in the experiment. A Co-60 is applied to simulate the irradiation background from 10–150 × 10^3 s^{-1} by varying its distance to the detector. A Cs-137 is placed at two positions in the vicinity of the detector to generate about 30 and 130 s^{-1} (dubbed as CS1 and CS2 in the text) counting rate in the FEP to mimic the situation of a low and a high burnup element, respectively (see next).

We first check the energy resolution and the throughput rate varying with the input counting rate. Fig. 2(a) depicts the throughput rate, defined by the ratio of the FEP counts recorded by the system over the real time, as a function of the average input rate expressed as the total counts divided by the live time recorded by the spectrometer. It is shown that at low radiation level the throughput rate exhibits a nearly linear increase commonly for the different shaping time. At about 100–120 × 10^3 s^{-1}, slightly depending on the settings of the amplifier, the throughput rate starts to deviate with different shaping time and undergoes a plateau up to an incident rate of about 200 × 10^3 s^{-1}, above which the throughput starts to decrease again due to the rapidly increasing dead time. While the maximum throughput rate decreases with the shaping time exponentially, as shown in Fig. 2(b), the full width at half maximum (FWHM) of the Cs-137 662 keV peak exhibits an increasing trend by increasing the input counting rate or switching down the shaping time, as shown in panel (c) and (d), respectively. Since an energy resolution better than 1.8 keV is required to discriminate the Cs-137 gamma peak from the background, particularly from the intense Nb-97 peak, the shaping time is set to $\tau_s = 0.8$ μs and the corresponding flattop time constant is $\tau_f = 0.8$ μs, respectively. In the following studies, the experiment results with this setting are presented.

Given the running parameters, the maximum incident radiation of about 120 × 10^3 s^{-1} is then fixed and leads to the design of the collimator. According to the simulation of the activities of all