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Investigations of sample reactivity worth measurement in a fast neutron reactor with the inverse kinetics method

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ABSTRACT

A new method for the measurement of sample reactivity worth in a fast neutron reactor named the inverse kinetics method is proposed in the paper. The sample reactivity worth could be obtained by measuring the reactivity step change in the process of sample fetching and placing in the delayed critical reactor. Compared with the traditional period method, the advantage is that the accuracy of reactor reactivity control will not exert any influence on the uncertainty of reactivity worth measurement. The inverse kinetics method has been used to measure the reactivity worth of Φ20 mm × 9 mm Au, V and Be samples at the center of the upper surface of a highly enriched uranium fast neutron reactor, and the results are 5.17¢, 4.40¢ and 5.90¢ respectively, which are consistent with those obtained with the period method. The standard uncertainty of measurement of the results is about 0.03¢, which achieves an obvious improvement compared with that (~0.08¢) of the period method.

1. Introduction

In the analysis of sensitivity and uncertainty, compared with the effective neutron multiplication factor k_{eff}, the sample reactivity worth is more sensitive to the change of neutron nuclear reaction cross section, and the uncertainty of cross section has more significant influence on the uncertainty of the sample reactivity worth calculation in the sensitivity and uncertainty analysis. Therefore, measurement of the sample reactivity worth has always been an important macro integral experiment for inspection and adjustment of neutron nuclear reaction cross section.

The period method and the reactivity compensation method (Engle et al., 1960; Sakurai et al., 2009; Casoli and Authier, 2007; Richard, 2012) are mainly used for the measurement of sample reactivity worth in a fast neutron reactor. These two methods have been brought into use since the 1950 s and never changed. Our research group studied the sample reactivity worth measurement with the period method on a highly enriched uranium fast neutron reactor in 2013 (Zhou, 2015; Zhou et al., 2016). The reactivity worth of 13 kinds of metal samples such as Au; Fe and Ni at the center of the reactor upper surface was obtained with a standard uncertainty of measurement of 0.08¢. It is found that the main source of the measurement uncertainty of the period method is the reactor's reactivity control accuracy due to positions non-repeatability of the main drive and control rods of the reactor.

In order to further reduce the uncertainty of measurement of the sample reactivity worth, a new method named the inverse kinetics method is proposed in this paper which is based on the inverse kinetics reactivity measurement technology. It will realize fast and accurate measurement of the sample reactivity worth by measuring the reactor's reactivity step change in the process of online sample fetching and placing in the delayed critical reactor. The method was used to measure the reactivity worth of the samples such as Au on the upper surface of the highly enriched uranium reactor. And the uncertainty of measurement was carefully evaluated.

2. Measurement system

2.1. Inverse kinetics measurement system

The inverse kinetics method is a conventional method for reactivity measurement. According to the point reactor kinetics equation, the inverse kinetics equation is written as (Takeuchi et al., 2000).

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$$\frac{\rho(t)}{\beta_{\text{eff}}} = 1 + \frac{\Lambda}{\beta_{\text{eff}} n(t)} \frac{dn(t)}{dt} - \frac{\Lambda}{\beta_{\text{eff}} n(t)} \sum_{i=1}^{M} \lambda_i e^{-\lambda_i t} C_i(t_0) - \frac{\Lambda q}{\beta_{\text{eff}} n(t)} - \frac{1}{\beta_{\text{eff}} n(t)} \sum_{i=1}^{M} \lambda_i \int_{t_0}^{t} \frac{\beta_i}{\Lambda} e^{-\lambda_i (t-\tau)} n(\tau) d\tau \quad (1)$$

where $n(t)$ is the neutron density, $\rho(t)$ is the reactivity, β_{eff} is the effective delayed neutron fraction, β_i is the delayed neutron fraction of the ith group, Λ is the neutron generation time of the reactor, C_i and λ_i are the density and decay constants respectively of the precursor of the ith group of delayed neutrons, M is the group number of the delayed neutrons, q is the outer neutron source intensity, and t is the time. For the fast neutron reactor used in the experiment, the $\Lambda\beta_{\text{eff}}$ is as small as 0.2×10^{-5}. The items including $\Lambda\beta_{\text{eff}}$ in Eq. (1) can be omitted for they are five orders of magnitude less than others. Therefore, the change in reactivity over time can be obtained while the reactor's power $n(t)$ is known.

The schematic of the inverse kinetics reactivity measurement system (Li et al., 2014) is shown in Fig. 1. Two independent identical detection systems were adopted for redundancy for they were used on a continued operating reactor and tested online. If there is only one, when it fails during the experiment, reactor need shut-up and restart and personnel will expose to radiation while enter the reactor hall to repair. The γ compensation-type ^{10}B ionization chambers are selected as the detectors, and the current signals are input to the industrial personal computer after being collected and converted by the programmable ammeters. The reactor's reactivity can be obtained from the Eq. (1) with the current and time data. The delayed neutron group parameters come from G. R. keepin's work (Keepin, 1965). The reactivity obtained according to Eq. (1) is a relative value in \$(1\$ = 100¢).

The statistical variance σ of reactivity measurement results with the inverse kinetics method is closely related to the current signal to noise ratio of the ionization chamber. The higher the neutron flux of the reactor, the smaller σ will be. Consequently, the reactor should operate at a stabilized power in a delayed critical state when the inverse kinetics method is used to measure the sample reactivity worth.

2.2. Online sample fetching and placing system

The experiment was performed in the reactor's delayed critical state. Personnel shall not enter the reactor hall during the experiment. Therefore, an online automatic sample fetching and placing system was developed for sample operation. The system consisted of control cabinet, controller, rotary dividing plate and manipulator (including a chuck, a cylinder that can moving up and down and a cylinder that can moving front and back), as shown in Fig. 2. The positioning accuracy of front, back, up and down transmission of the manipulator was 0.02 mm. The rotary dividing plate with six storage positions was used for storage and automatic shift of samples and the tilt angle positioning accuracy was higher than 0.03°. The manipulator was installed next to the reactor and the chuck was 50 cm from the reactor center. In order to realize automatic fetching and placing of sample between the sample groove of reactor and the rotary dividing plate, the rotary dividing plate and the upper surface of the reactor should be at the same level. Meanwhile, adjust the chuck, the rotary dividing plate's sample groove and the reactor's sample groove in a straight line by fine adjustment of the base position. The manipulator's control cable was laid out to the reactor control room, and a remote operation was done by a controller. A HD camera was installed near the reactor to make a real-time monitoring for the sample fetching and placing process in the control room during the experiment.

3. Experimental method

The experiment was performed on a highly enriched uranium (HEU) fast neutron reactor (Zhou et al., 2016). The core is composed of a control rod, a lower active zone, a middle steel disc, an upper active zone and reactivity adjustment components. There are four HEU reactivity adjustment ring components A, B, C and D at the top of the upper active zone. Another four components had been manufactured in the same dimensions but with stainless steel metal. The reactivity could be controlled by each adjustment component's presence and absence or changing its material. The center of the lower active section is a HEU metal control rod.

The experimental was conducted at the center of the upper surface of the reactor. The adjustment components A and B were removed and replaced by stainless steel components with a sample groove which was Φ20.00 mm and 9.00 mm in depth. The samples, which were high purity Au, V and Be materials with the impurity content less than 0.01% provided by Beijing General Research Institute of Nonferrous Metals, were Φ19.98 mm and 9.00 mm thick.

In the experiment process, an Au sample was placed in the sample groove at first, and the reactor was operated to the delayed critical state with the power 30 W and reactivity $\rho_{1,1}$ (thereafter, the reactivity under the same state should be denoted by $\rho_{1,i}$ in sequence, $i = 1,2,\ldots,10$). Afterwards, the Au sample was taken away. A positive step of reactivity with a very short time was recorded when the manipulator got near the sample which results

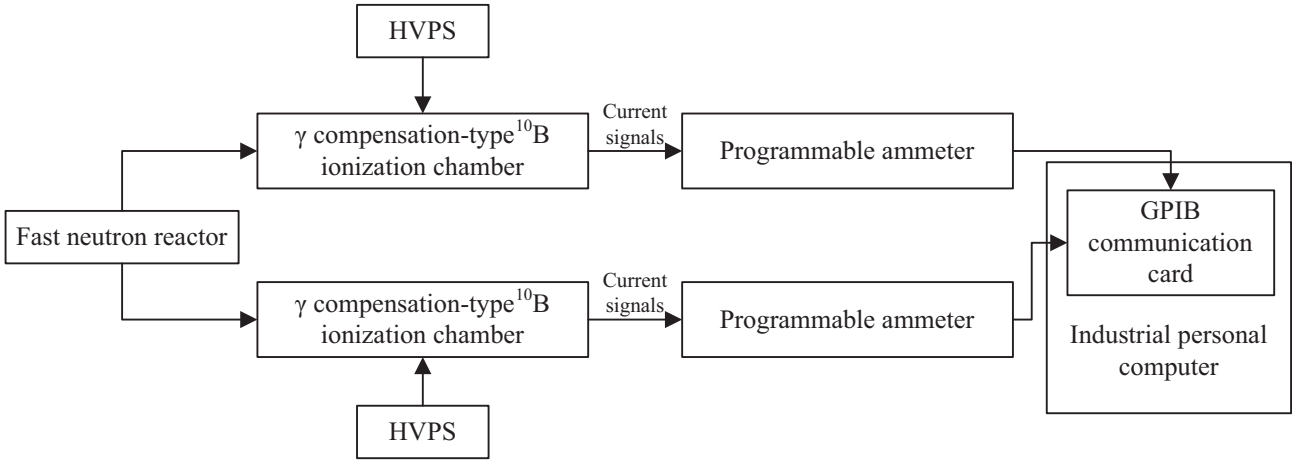

Fig. 1. Schematic structure of reactivity measurement system with the inverse kinetics method.