Measurement of Boron Concentration with the Serpentuator System

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Abstract — *An off-line boron meter in a pressurized water reactor (PWR) nuclear power plant has the disadvantages of lagging data measurements and a long response time. This paper aims to shorten the response time and enhance the measurement accuracy of this type of device. First, the shortcomings of off-line boron meters were analyzed and the serpentuator system was proposed to replace the typical container system. Then, both FLUENT and GEANT simulation tools were used to demonstrate the merits of the serpentuator system. FLUENT was used to simulate the fluid response, while GEANT4 was used to obtain the f(P) curve. The simulation results from FLUENT indicate that the residence time of the fluid in the container system was approximately 9.5 times that in the serpentuator system. The simulation results obtained from GEANT4 manifest that the f(P) curve of the rectangular section was steeper than for the circular section. When the polyethylene was 8 cm thick, the f(P) curve was the steepest. Compared with a serpentuator made of titanium alloy, stainless steel, and brass, a serpentuator made of zirconium alloy or aluminum alloy achieved a steeper f(P) curve. Therefore, the serpentuator system is more applicable for PWRs using an off-line boron letdown through a chemical and volume control system.*

Keywords — *Boron meter, serpentuator system, FLUENT.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

During the normal operation of a pressurized water reactor (PWR) nuclear power plant, the reactor must be maintained in a critical state where the reactivity equals zero. The state is mainly controlled by three reactivity control modes: the control rod, burnable poison, and borated coolant.[1] The borated coolant control mode is the most important mode.[2] Therefore, continuous real-time monitoring of the boron concentration in the coolant is a vital task to ensure safe operations of the reactor. Moreover, the boron meter is a dedicated device for real-time monitoring of the boron concentration in the coolant.[3]

There are off-line and online types of boron meter in a nuclear power plant, which can measure the boron concentration in the reactor. The significant difference between the two types is whether a sampling procedure is required. The measurement device of an online boron meter is installed on the outer surface of the letdown pipeline in the chemical and volume control system[4] and gives quick responses.[5] However, in an off-line boron meter, the boron solution is guided into a special room to be measured through a special sampling line, which leads to a long response time.[6]

Two causes are responsible for the long response time of an off-line boron meter. First, the long sampling line is inherent in the off-line type. Second, the special structure of the measurement device requires a long measurement time.[5] To shorten the response time, a serpentuator system

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was proposed to replace the typical container system based on an analysis of the measuring principle and structural features of a typical off-line boron concentration device. In this paper, we analyzed the serpentuator system for shortening the response time and enhancing measurement accuracy.

II. MEASURING PRINCIPLE AND DEFECTS OF TYPICAL OFF-LINE BORON METERS

A typical off-line boron concentration measurement device is depicted in Fig. 1. Samples separated from the primary loop flow through a thin sampling tube and into an off-line container system at the chemical processing facility outside the primary loop. The average thermal neutron capture cross section for ^{10}B is up to 3837 b (Ref. 7). Neutrons passing through the container wall are moderated and absorbed in the boron solution and finally are detected by the neutron counter tube whose pulse signal reflects the counting rate of neutrons. $^{10}B(n, \alpha)^{7}Li$ reactions[8] are expressed as

$$n + {}^{10}B \rightarrow \alpha + {}^{7}Li + 2.792\ \text{MeV}\ (6.1\%) \tag{1}$$

and

$$n + {}^{10}B \rightarrow \alpha + {}^{7}Li^{*} + 2.31\ \text{MeV}\ (93.9\%)\ . \tag{2}$$

When the boron concentration changes, the number of neutrons entering the neutron counter tube changes, thus changing the number of absorbed thermal neutrons. Therefore, the neutron count rate obtained through signal acquisition varies with the boron concentration. Conversely, measurement of the neutron count rate can steadily measure the boron concentration in the primary loop of the reactor.

The relationship between pulse counting rate and boron concentration is expressed as

$$f(P) = n = n_0 e^{-\lambda P}\ , \tag{3}$$

where

P = boron concentration

n = neutron count rate detected by the neutron counter tube when the boron concentration is P

n_0 = neutron count rate without boron in the solution

λ = a constant associated with the structure of the measurement device, which can be used to characterize the function attenuation speed.[6]

The second-order Taylor expansion of Eq. (3) is expressed as

$$f(P) = n = n_0\left(1 - \lambda P + \frac{\lambda^2}{2}P^2\right)\ . \tag{4}$$

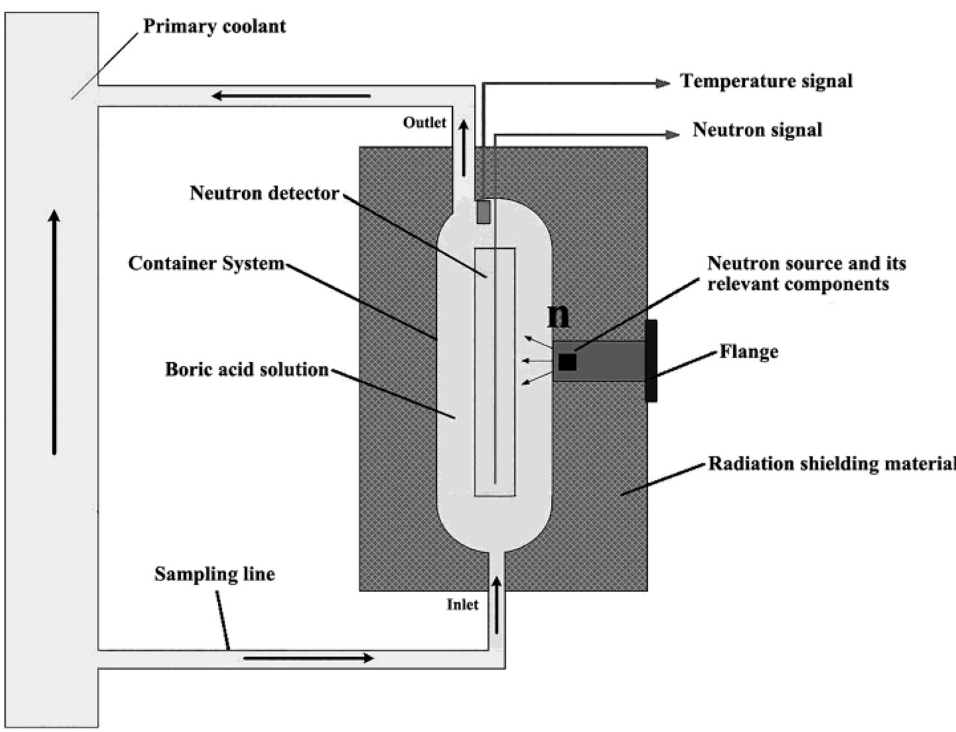

Fig. 1. Schematic of an off-line container-type boron concentration meter.

If we impose $a = \frac{n_0\lambda^2}{2}$, $b = -\lambda n_0$, and $c = n_0$, then Eq. (4) can be rewritten as

$$f(P) = n = aP^2 + bP + c \ . \tag{5}$$

When a sequence of (P, n) has been measured through the calibration test with the boron concentration meter, the coefficients a, b, and c can be determined by fitting Eq. (5) with the least-squares method.

To enhance the utilization of the boron solution and decrease the disturbance caused by the scattering neutrons outside of the container, the neutron detector must be installed inside the container (Fig. 2). Neutrons received by the neutron detector are all attenuated by the boron solution for noninterference counting, thus realizing the high utilization of the neutron source.

The typical container system in an off-line boron meter is approximately cylindrical (Fig. 3). When the boron solution enters the container from the bottom, due to the sudden increase in the cross-sectional area, the flow rate of the boron solution in the container becomes slow. Then, the solution near the walls and especially at the corners is likely to be motionless or isolated from the main bulk flow. These regions form a dead zone. Therefore, the residence time of the boron solution in the measuring container is quite long. The long residence time is not conducive to real-time measurement.

III. SERPENTUATOR BORON METER AND ITS ADVANTAGES

To reduce the data measurement lag of the typical off-line boron meter, the serpentuator system is proposed in this study, as depicted in Fig. 4.

The neutron counter tube is twined by the serpentuator system, which can fully receive thermal neutrons attenuated by the boric acid solution around the neutron

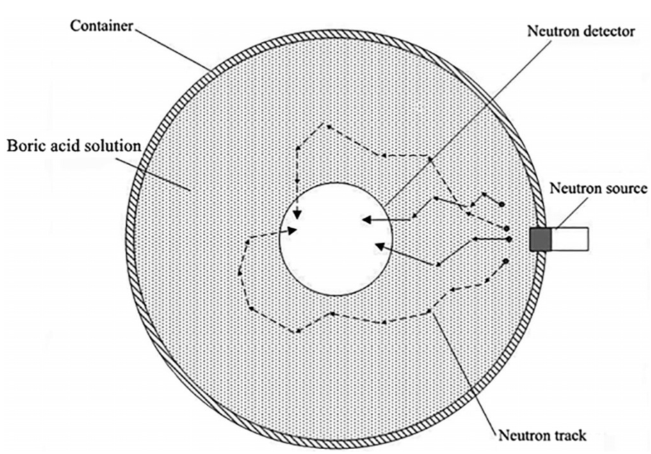

Fig. 2. Neutron track diagram.

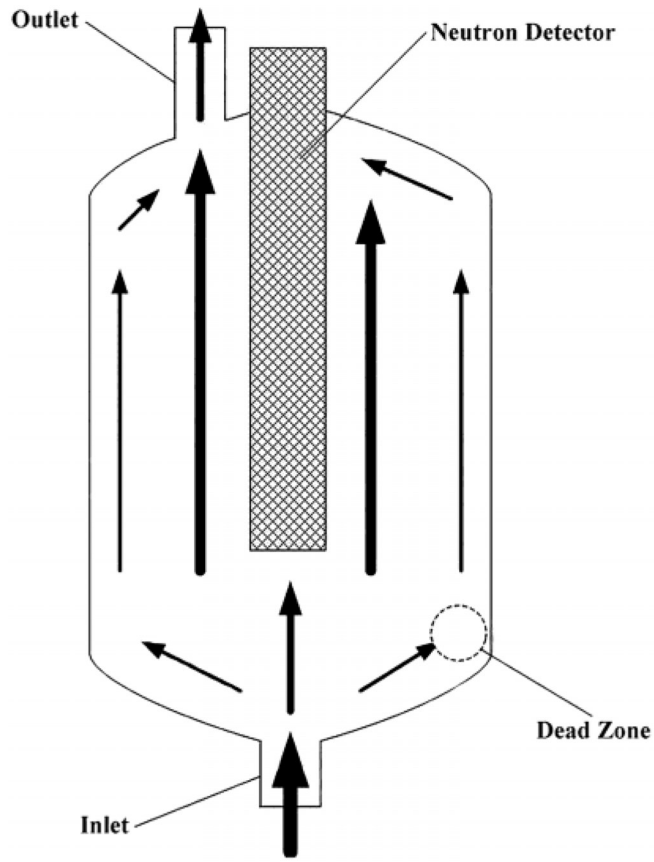

Fig. 3. Solution motion in the container system.

counter tube, thus reducing the counting interference and increasing the utilization of the neutron source. The serpentuator is surrounded by a moderation layer that can slow fast neutrons emitted by neutron sources to form thermal neutrons to improve the counting rate. The shielding layer around the moderation layer is made of boron-doping polyethylene, which ensures that the device can satisfy the surface dose limit.

IV. RESIDENCE TIME COMPARISON

To compare the serpentuator system with the container system in terms of residence time of the boric acid solution, the fluid response in these two models was simulated with FLUENT (ANSYS, Inc., Version 14.0). The following model was established under the same conditions. The inlet and outlet pipes had the same cross-sectional area. The average flow rate at the inlet was 10 m/s and the boric acid concentration was 3000 ppm. If pure water was injected into the container, then the original boric acid solution was thought to be replaced approximately by pure water when the boric acid concentration was gradually diluted from 3000 ppm to close to 0 ppm.

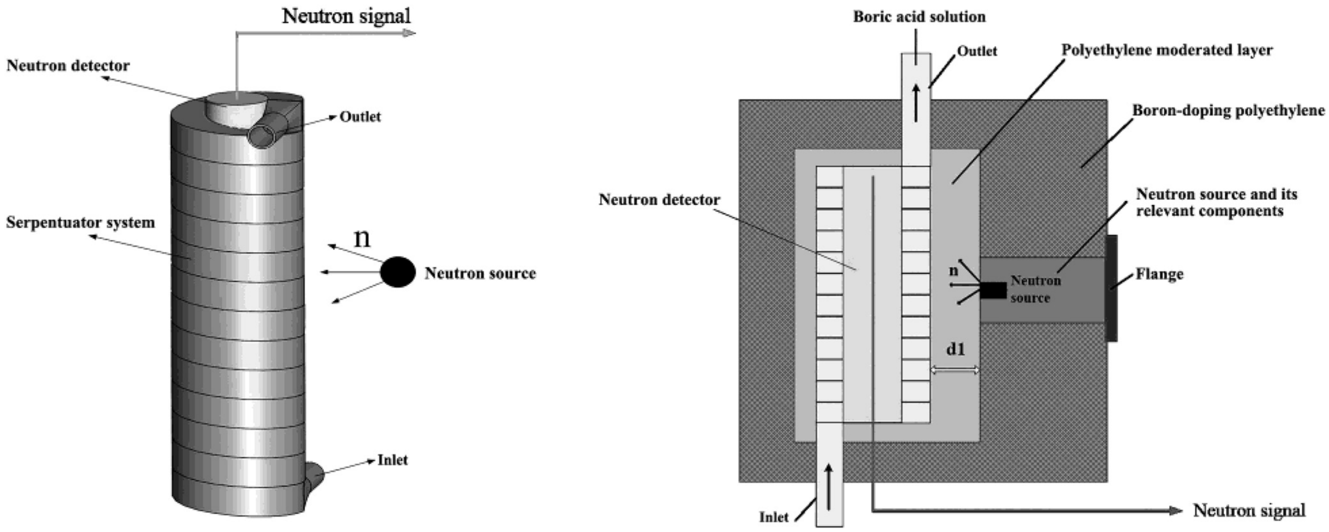

Fig. 4. Schematic of a boron meter utilizing the serpentuator system.

The variation of the residual boric acid solution with time in both the container system and the serpentuator system was simulated with FLUENT software (Fig. 5).

Figure 6 depicts the simulation results. When the boron concentration is close to 0 ppm, the residence time of the fluid in the container system is approximately 9.5 times that in the serpentuator system, suggesting that for an off-line boron meter the serpentuator system is characterized by a faster response and a shorter residence time.

The comparison in Fig. 6 can be interpreted in three aspects. First, the cross sections of the serpentuator and the sampling line are very similar so that the fluid velocity remains basically unchanged. Second, the inner volume of the serpentuator is relatively small and the serpentuator is less affected by diffusion of the solution. Third, it is difficult to form a dead zone in a serpentuator system.

V. EFFECTS OF SERPENTUATOR MEASUREMENT DEVICE ON λ

The steepness of the $f(P)$ curve is associated with the constant λ. A bigger λ means a steeper $f(P)$ curve as well as a higher measurement accuracy of the boron meter. To achieve a larger λ, the GEANT4 simulation tool[9,10] (a Monte Carlo radiation transport code from CERN, Version 9.6) was used to study separately the influence of the following three essential factors on λ: the shape of the serpentuator, the moderation distance between the neutron

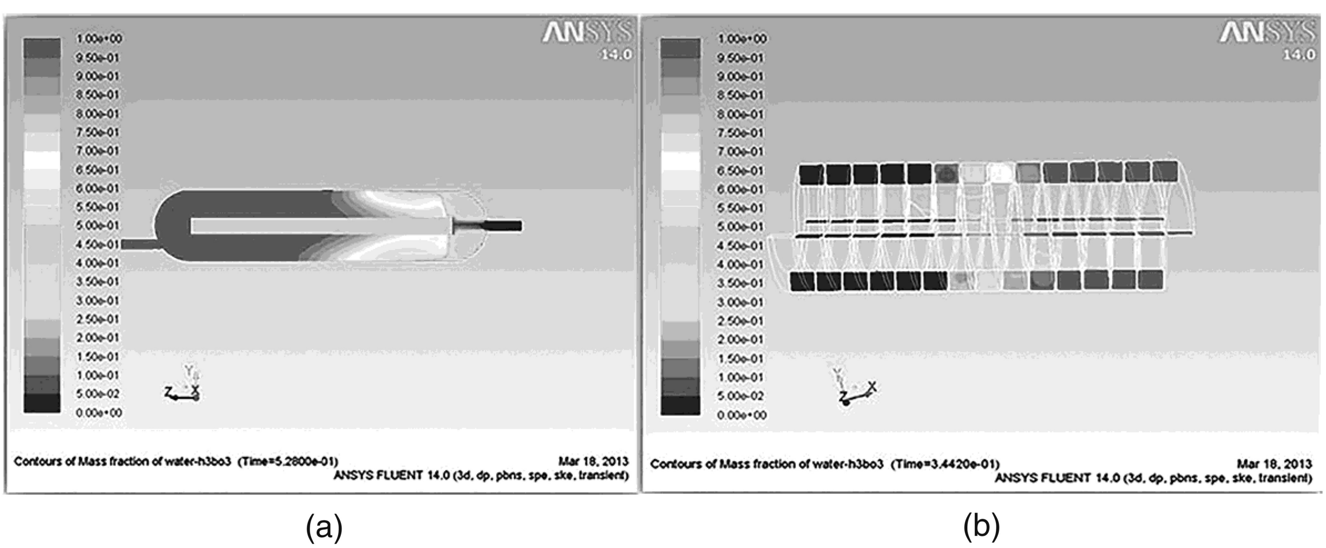

Fig. 5. Boric acid solution flowing in (a) the container system and (b) the serpentuator system.

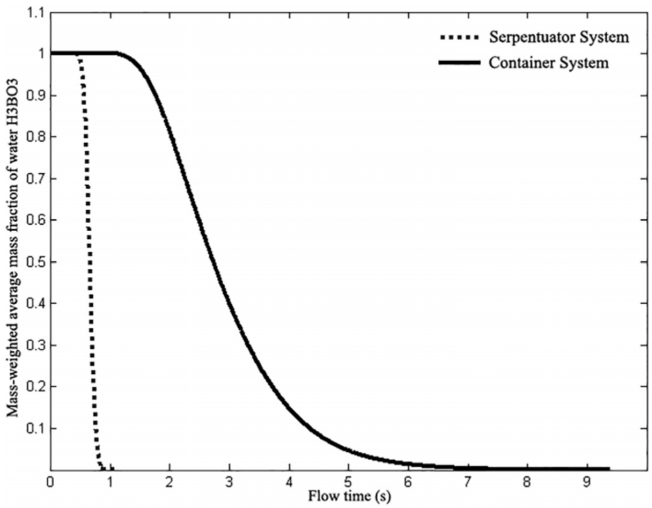

Fig. 6. Comparison of fluid response between the serpentuator and container systems.

source and the serpentuator, and the material of the serpentuator.

V.A. GEANT4 Simulation Condition and Feasibility Analysis

When setting the simulation conditions of a boron meter in GEANT4, neutrons can be generated through an americium-beryllium (Am-Be) neutron source (regarded as a point source).[11] Its energy spectrum is depicted in Fig. 7. The neutron counter tube is a cylindrical BF_3 proportional counter. The gas density is 0.002786 g/cm^3, and the sensitive volume is of diameter 50 mm and length 450 mm. Austenitic steel was chosen as the wall material with thickness of 1.5 mm.

According to Eqs. (1) and (2), the energy of ^{7}Li and alpha particles are 1.015 MeV and 1.777 MeV,

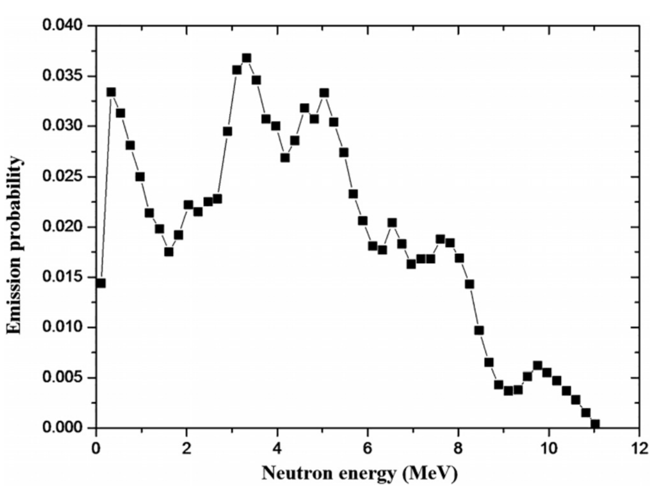

Fig. 7. Energy spectrum of Am-Be neutron source.

respectively.[12] The ranges of ^{7}Li and alpha particles in the sensitive volume were respectively calculated to be 3.56 mm and 4.78 mm with the SRIM software.[13] The calculated ranges were far less than the size of the counter's sensitive volume. Additionally, ^{7}Li and alpha particles are heavily charged particles with limited penetration capacity, and it is believed that Li and alpha particles cannot penetrate through the walls of the counter tube.[14] Therefore, each (n, α) reaction in the proportional counter tube can output a pulse count,[15] and the times of the (n, α) reaction can be calculated. That is to say, the pulse counting can be achieved based on GEANT4.

The variation of the neutron count rate with the boron concentration can be obtained by changing the boron concentration (0 to 4000 ppm). Since both neutrons emitted by the neutron source and the $^{10}B(n, \alpha)^7Li$ reaction were randomly generated, the counting result (the number of α deposited) obtained through the simulation showed a statistical fluctuation. To reduce the statistical fluctuation of counting, it is possible to increase the number of incident particles and calculate the average value of multiple simulations[16] to obtain a smooth $f(P)$ curve.

V.B. Cross-Sectional Shape of Serpentuator System

The cross-sectional shape of the serpentuator is usually rectangular or circular[17] (Fig. 8). With the same cross-sectional area and wall thickness, two models were built based on GEANT4 to analyze the variation of the times of the (n, α) reaction (pulse counting) with boron concentration.

Figure 9 represents the (n, α) reaction process in the serpentuator system in a split second. The red points indicate negatively charged particles, the green points indicate neutral particles, and the yellow points indicate the steps.[9]

A rectangular cross section gives a larger λ than a circular one. That is to say, the $f(P)$ curve is steeper, as plotted in Fig. 10.

The steepness of the $f(P)$ curve is mainly affected by the following two factors:

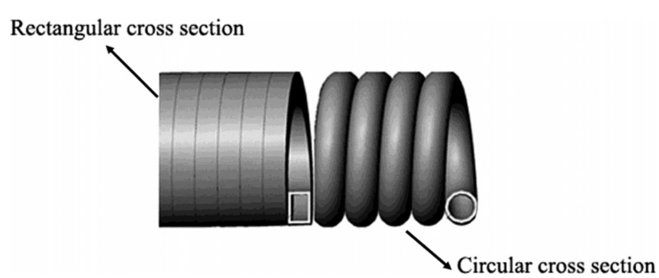

Fig. 8. Rectangular and circular cross sections of the serpentuator system.

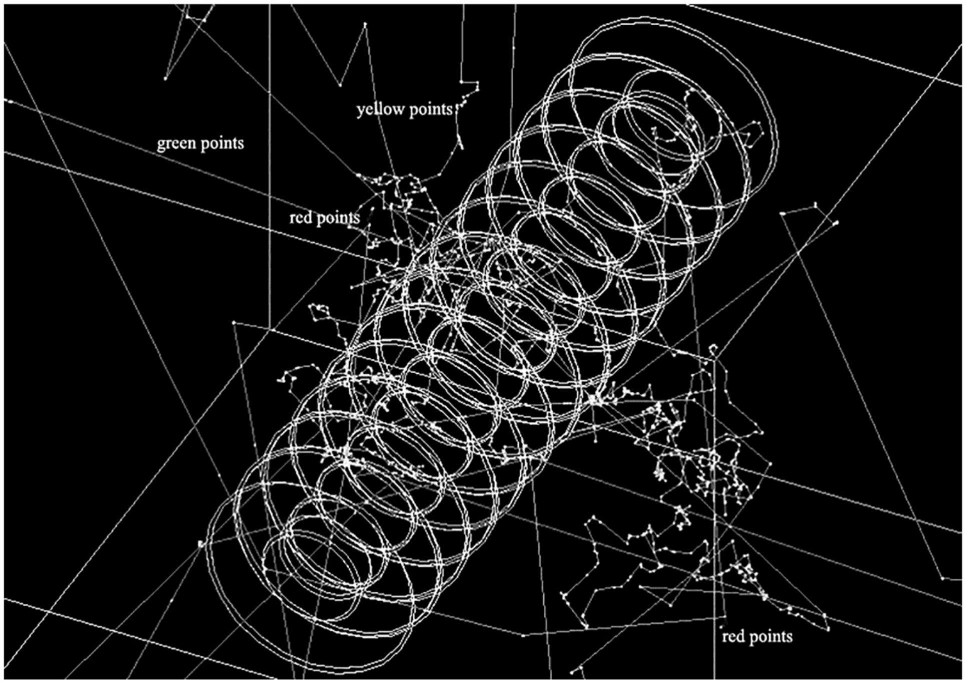

Fig. 9. (n, α) reaction process in the serpentuator system in a split second.

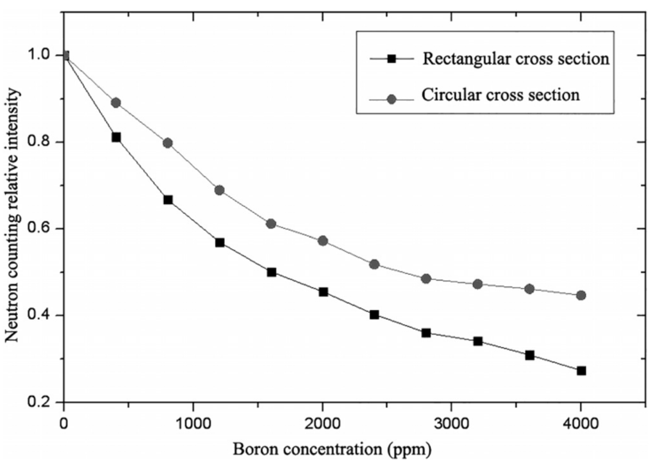

Fig. 10. Effects of different cross sections on $f(P)$ curve.

1. Radial penetration distances of neutrons in the boric acid solution. For a serpentuator with a circular cross section, each lap has a long middle and short sides, which can result in an uneven radial distance when thermal neutrons penetrate the boron solution before they enter the proportional counter. The radial distance of each lap is the largest in the center and gradually decreases toward both sides. For a serpentuator with a rectangular cross section, the radial distance of each lap is a constant.

2. Wall gaps. For the serpentuator with a circular cross section, partial neutrons can directly pass through the gap and enter the neutron counting tube without entering the boron solution. The counting caused by the above neutrons is invalid counting. However, for the serpentuator with a rectangular cross section, the pipe gap is narrow. Therefore, the variation of neutron count rate with the boron concentration has relatively higher sensitivity.

V.C. Moderation Layer Thickness

Neutrons emitted by an Am-Be source are mostly fast neutrons. To make more thermal neutrons enter the serpentuator system, it is required to add a moderation layer between the neutron source and the pipeline. The moderation layer is usually made of hydrogen-rich materials with a small absorption cross section and a large scattering cross section.[18] Polyethylene is rich in hydrogen and it is simple to process. Polyethylene is a favorable neutron moderation material.[19] Therefore, polyethylene is a superior choice as the moderation material between the neutron source and the serpentuator system. The influence of polyethylene thickness on the $f(P)$ curve was simulated with GEANT4. Figure 11 depicts that the steepness of the $f(P)$ curve varies with polyethylene thickness.

The polyethylene thickness directly affects the energy spectrum of the neutrons. A smaller or larger polyethylene thickness may decrease the number of neutrons entering the serpentuator system, and then fewer low-energy neutrons may be detected in the counting tube. An 8-cm-thick polyethylene moderation layer gave the optimal neutron spectrum and the steepest $f(P)$ curve.

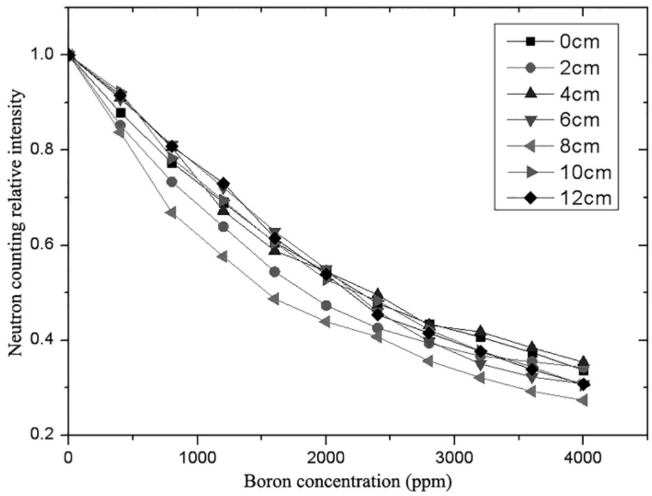

Fig. 11. Effects of polyethylene thickness on $f(P)$ curve.

V.D. Serpentuator Material

The effects of titanium alloy, stainless steel, aluminum alloy, zirconium alloy, and brass on the $f(P)$ curve was studied with GEANT4. The steepness of the $f(P)$ curve varied with the material of the serpentuator (Fig. 12), and aluminum and zirconium alloy gave a much steeper $f(P)$ curve.

VI. CONCLUSION

The off-line boron meter has the disadvantages of lagging data measurements and poor real-time performance, which mainly result from the long sampling line and the structure of the measurement device. To improve the measurement device, a serpentuator system is proposed as a replacement for the container system. It can reduce the residence time of the fluid in the boron meter and shorten the response time.

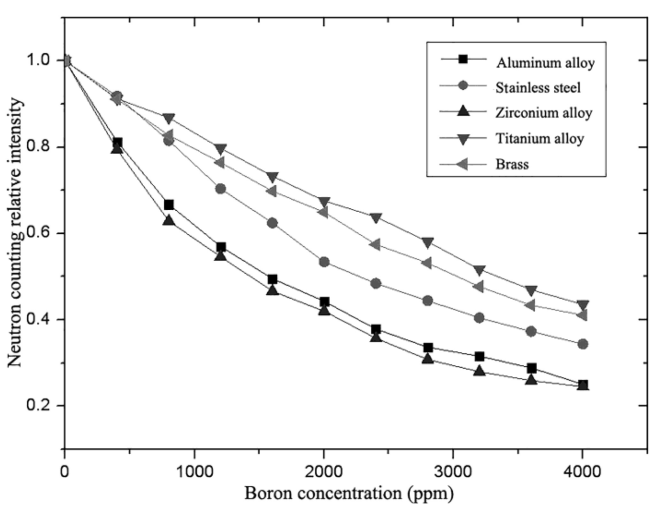

Fig. 12. Effects of different serpentuator materials on $f(P)$ curve.

In this paper, the FLUENT and GEANT4 simulation tools were used to demonstrate the merits of the serpentuator system. The fluid response and neutron response were simulated in FLUENT and GEANT4, respectively. First, the simulation results obtained with FLUENT demonstrated that the residence time of the fluid in the container system was approximately 9.5 times that in the serpentuator system, indicating a remarkably fast response in the serpentuator system. Second, GEANT4 was used to investigate the impact of serpentuator shape, thickness of polyethylene moderation layer, and serpentuator material on the steepness of the $f(P)$ curve. With the same wall thickness and cross-sectional area, the $f(P)$ curve was steeper for a serpentuator with a rectangular cross section. When the polyethylene was 8 cm thick, the $f(P)$ curve became the steepest. Compared with a serpentuator made of titanium alloy, stainless steel, or brass, a serpentuator made of zirconium alloy or aluminum alloy gave a steeper $f(P)$ curve.

Nevertheless, the study in this paper mainly depends on theory and software simulation because it is rather difficult to realize the experimental conditions (neutron source, machining the parts of the detector device, etc.). The results undoubtedly provide the basis for improving the off-line boron meter in a PWR nuclear power plant.

Acknowledgments

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