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High accuracy boronometer design developed for light water reactors

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A B S T R A C T

This paper presents a new high accuracy boronometer design with two optimized features: a minimized error for signal-to-boron concentration conversion and high accuracy boron concentration measurements by two-range detection. The design optimization was performed using four boronometer models that are combinations of single- and two-range detectors and high- and low-sensitivity detectors manufactured by LND and IST Inc. The boronometer's accuracy was evaluated by the root mean square (RMS) error of conversion function fitting and the RMS error of measured boron concentrations. The rational function with a 0th order polynomial in the numerator and a 4th order polynomial in the denominator showed the smallest RMS fitting error, and the two-range boronometer model with four low-sensitivity detectors (11.3 cps/nv) and two high-sensitivity detectors (28.0 cps/nv) showed the smallest RMS error for boron concentration measurement.

1. Introduction

Boronometers have been used to measure the boron concentration in the reactor coolant system of pressurized water reactors (PWRs) (Wong, 1984). It is highly recommended that operators are well-informed about the boron concentration to ensure the safety of core physics tests, fuel reloading, and normal operations (Kim et al., 2015). Two methods are used to measure the boron concentrations in a reactor coolant system: chemical titration and boronometer measurement (Coulman, 1964; Rhee et al., 2014). The chemical titration method is well known for its high accuracy (Chen et al., 2010); however, it produces radioactive waste from coolant samples and has a long turn-around time. Although the boronometer has continuous monitoring capability, the accuracy of its measurements is low, and therefore, there has been a strong demand to improve its accuracy (Zubair et al., 2014).

Several studies on the boron concentration in reactor coolant systems have been performed to investigate its impact and to reduce the corrosion issues caused by the boric acid. The effects of the boron concentration in a reactor coolant system have been investigated on the effective neutron multiplication factor, k_{eff}, the prompt neutron lifetime, and the effective delayed neutron fraction (Thong et al., 2016). A boron-free small modular PWR has been designed to reduce the size of a nuclear power plant and the amount of radioactive waste it generates (Choe et al., 2016).

Boronline, a boronometer developed by Rolls-Royce, is the latest generation of boronometer (Pirat, 2011). It allows real-time measurements of boron concentration and data processing necessary for safe reactor operation. Several preliminary studies have been performed to improve the accuracy of boronometers. Lee et. al. performed sensitivity analysis on one-dimensional boric acid slabs of different thicknesses (Lee et al., 2013). Kong et. al. performed sensitivity analyses on boronometer geometry and evaluated several conversion functions (Kong et al., 2015a,b). We performed a boronometer optimization test as a preliminary study (Kong et al., 2016a). Kong et. al. also reported a boronometer model with a simple fitting function error comparison and two-range concept, but used commercially unavailable detector specifications in the design (Kong et al., 2016b). The comparison was performed only with the data fitting errors at 18 boron concentrations, which shows how accurately the conversion function represents data points. The 18 boron concentrations are 0, 10, 50, 100, 250, 500, 750, 1000, 1250, 1500, 1750, 2000, 2250, 2500, 2750, 3000, 4000 and 5000 ppm.

The novelty of this study is that the comparison is performed with a new performance index, i.e., the measured boronometer concentration errors and the data fitting errors. In addition, the boronometer in this study has been further optimized with commercially available high-sensitivity ^3He and BF_3 detectors manufactured by IST and LND Inc., whereas boronometers in the previous study (Kong et al., 2016b) were based on artificial detector specifications.

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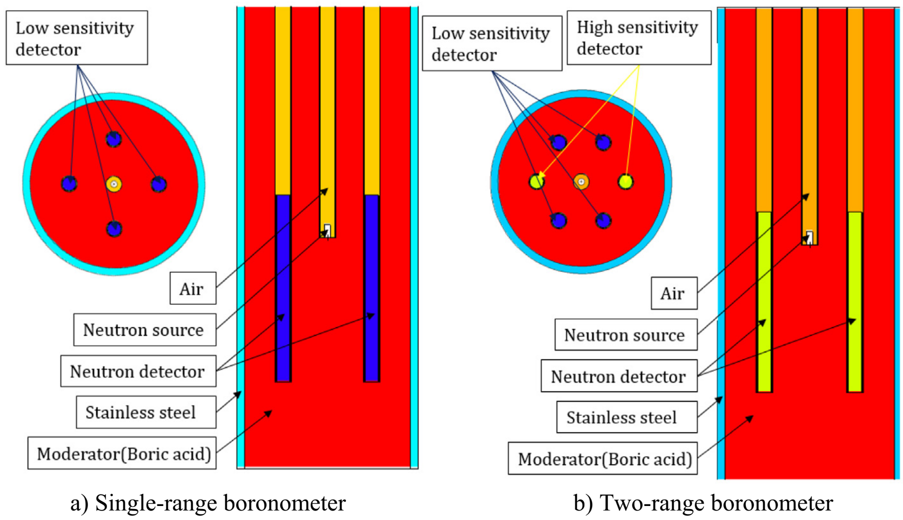

Fig. 1. Geometry of two boronometer designs.

Table 1
Detector specifications.

Detector type	IST_BF3_4.0	LND_BF3_4.0	LND_BF3_11.3	LND_He_28.0
Gas	BF_3	BF_3	BF_3	^3He
Sensitivity [cps/nv]	4.0	4.0	11.3	28.0
BF_3 (or ^3He) gas density [g/cm^3]	0.001443	0.001168	0.002858	0.0003516
Effective length [mm]	215.9	265.7	311.0	203.2
Cathode inner radius [mm]	24.03	24.03	24.03	24.03
Cathode outer radius [mm]	25.40	25.40	25.40	25.40

Table 2
Boronometer model.

Model	Detector type used in boronometer (#)	Boron concentration range [ppm]	Neutron detector usage
Single_4.0	IST_BF3_4.0 (4)	0–5000	IST_BF3_4.0
Two_4.0 + 11.3	LND_BF3_4.0 (4)	0–1500	LND_BF3_4.0
	+LND_BF3_11.3 (2)	1500–5000	LND_BF3_4.0, LND_BF3_11.3
Two_4.0 + 28.0	LND_BF3_4.0 (4)	0–1500	LND_BF3_4.0
	+LND_He_28.0 (2)	1500–5000	LND_BF3_4.0, LND_He_28.0
Two_11.3 + 28.0	LND_BF3_11.3 (4)	0–1500	LND_BF3_11.3
	+LND_He_28.0 (2)	1500–5000	LND_BF3_11.3, LND_He_28.0

2. Optimization of boronometer design

An optimization study has been performed with the MCNP6 Monte Carlo code developed by the Los Alamos Laboratory (MCNP6 User's Manual, 2013) to develop new boronometers that can measure on-line boron concentrations with high accuracy. Fig. 1 shows the geometry of the boronometers. The boronometer with single-range detectors shown in Fig. 1a consists of four neutron detectors and an Am-Be neutron source at the centre. The boronometer with two-range detectors shown in Fig. 1b consists of six neutron detectors, i.e., four low-sensitivity detectors and two high-sensitivity detectors. The two boronometers differ in the number of detectors they consist of and in the detectors' sensitivities. Two additional high-sensitivity detectors are added to detect neutrons efficiently even when the neutron flux level is low.

2.1. Neutron detector model

Neutrons can be detected indirectly by using the charged particles they generate during nuclear reactions, such as Eqs. (1) and (2). Eq. (1) shows the (n, α) reaction of the BF_3 detector, and Eq. (2) shows the (n, p) reaction of the ^3He detector.

$$^{10}_{5}B + n \rightarrow \begin{cases} \alpha + ^{7}_{3}Li + 2.310\text{ MeV } (94\%) \\ \alpha + ^{7}_{3}Li + 2.792\text{ MeV } (6\%) \end{cases} \quad (1)$$

$$^{3}He + n \rightarrow p + ^{3}H + 765\text{ keV} \quad (2)$$

The number of detector signals is equal to the number of (n, α) reactions and (n, p) reactions in the BF_3 detector and ^3He detector, respectively. The (n, α) reactions and (n, p) reactions are tallied by the fm4 tally function of MCNP6, and considered as the neutron count rate.

Table 1 shows the specifications of the detectors used in the boronometers in Fig. 1. The name of each detector type is in the form of X_Y_Z; X is the manufacturer, Y is the filling gas, and Z is the detector sensitivity. The specifications of the detector models

Table 3
Conversion functions.

Boronline	$P = \dfrac{1}{A_1X^2 + A_2X + A_3}$	(3)
R-1-2	$P = \dfrac{A_1 + A_2X}{A_3X^2 + A_4X + 1}$	(4)
R-0-3	$P = \dfrac{1}{A_1X^3 + A_2X^2 + A_3X + A_4}$	(5)
R-0-4	$P = \dfrac{1}{A_1X^4 + A_2X^3 + A_3X^2 + A_4X + A_5}$	(6)