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Original Article

Accuracy Improvement of Boron Meter Adopting New Fitting Function and Multi-Detector

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ABSTRACT

This paper introduces a boron meter with improved accuracy compared with other commercially available boron meters. Its design includes a new fitting function and a multi-detector. In pressurized water reactors (PWRs) in Korea, many boron meters have been used to continuously monitor boron concentration in reactor coolant. However, it is difficult to use the boron meters in practice because the measurement uncertainty is high. For this reason, there has been a strong demand for improvement in their accuracy. In this work, a boron meter evaluation model was developed, and two approaches were considered to improve the boron meter accuracy: the first approach uses a new fitting function and the second approach uses a multi-detector. With the new fitting function, the boron concentration error was decreased from 3.30 ppm to 0.73 ppm. With the multi-detector, the count signals were contaminated with noise such as field measurement data, and analyses were repeated 1,000 times to obtain average and standard deviations of the boron concentration errors. Finally, using the new fitting formulation and multi-detector together, the average error was decreased from 5.95 ppm to 1.83 ppm and its standard deviation was decreased from 0.64 ppm to 0.26 ppm. This result represents a great improvement of the boron meter accuracy.

1. Introduction

In pressurized water reactors (PWRs) in the Republic of Korea, boron meters have been used to estimate the boron concentration in the reactor coolant [1]. It is essential to continuously monitor boron concentration during normal operation because the excess reactivity of the core is compensated by the boric acid. Furthermore, during a core physics test or fuel reloading, to ensure safe operation, it is highly recommended that operators are well-informed of boron concentration in the coolant [2].

There are two ways to measure boron concentration in the reactor coolant: one is a periodic chemical sampling and the other is a boron meter prediction [3,4]. In terms of measurement accuracy, it is well-known that the chemical sampling method performs much better than the boron meter [5]. However, in

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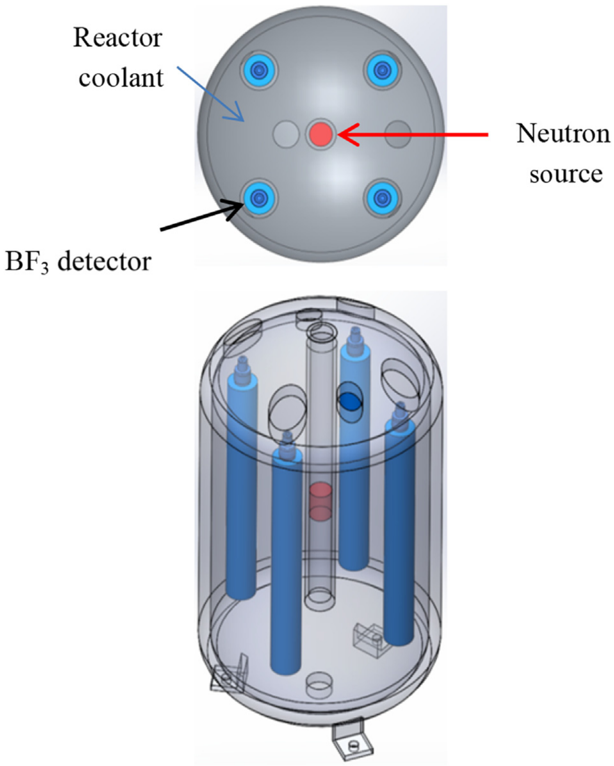

Fig. 1 – Boron meter geometry.

terms of continuous monitoring, the sampling method requires samples of reactor coolant for each measurement and is therefore inconvenient compared with the boron meters. As boron meters have the advantage of continuous monitoring compared with the sampling method, there has been a strong demand to improve the accuracy of boron meters [6].

To improve the accuracy of boron meters, several preliminary tests were performed: Lee et al [7]. tried to perform sensitivity tests on a one-dimensional boric acid slab of different thicknesses. Kong et al [8] performed sensitivity analysis on boron meter geometry and then evaluated diverse fitting functions [9]. Also, boron meter optimization was studied as preliminary study of this work [10]. In this paper, a boron meter evaluation model was developed, and two approaches were studied to improve the boron meter accuracy: the first one consists of applying a new fitting function and the second one uses a multi-detector. Section 2 describes a boron meter evaluation model using a Monte Carlo code. Section 3 introduces diverse fitting functions and their performances. Section 4 represents a multi-detector and its performance when the count signal is contaminated with noise such as field measurement data. Section 5 describes the conclusions derived from the two new approaches and corresponding results.

2. Boron meter evaluation model

2.1. *Boron meter Monte Carlo model development*

A boron meter is composed of an *Am-Be* neutron source located at its center and four BF_3 detectors are positioned surrounding the source as in Fig. 1. The radius and height of the boron meter are 12.7 cm and 55 cm, respectively, and the material surrounding the source and detectors is stainless steel.

Tables 1 and 2 show the geometry and material density of the boron meter, respectively. This model was calculated with the MCNP6 Monte Carlo code developed by Los Alamos National Laboratory [11]. The detailed model will be described in next sections.

2.2. *Am-Be neutron source model development*

The *Am-Be* neutron source generates neutrons based on Eqs. (1) and (2). Eqs. (1) and (2) show the alpha particle generated from *Am* decay and collision of that alpha particle with *Be*, respectively. When 1 Ci (3.7×10^{10} Bq) neutron source is used, 2.4×10^6 neutrons are emitted. Fig. 2 shows the *Am-Be* neutron spectrum as determined with a SCALE/ORIGEN 1-day depletion calculation [12].

$$^{241}_{95}Am \rightarrow ^{237}_{93}Np + ^{4}_{2}He, \tag{1}$$

$$^{9}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + n. \tag{2}$$

2.3. *BF_3 detector model development*

The detection principle of the BF_3 detector is an alpha particle generated by ^{10}B absorption, as in Eq. (3), ionizes surrounding particles, and those ionized particles are converted to a current signal by the voltage inside the detector. As the detection number is equal to the (n,α) reaction numbers, the (n,α) detection rates tallied by the MCNP6 fm4 tally function are used as neutron count rates. The standard deviations of all tallied counts are smaller than 0.06%, which is small enough to be neglected. Fig. 3 shows the tallied count rate according to boron concentration.

$$^{10}_{4}B + n \rightarrow ^{7}_{3}Li + ^{4}_{2}He. \tag{3}$$

3. Fitting function optimization

3.1. *Fitting procedure*

The fitting procedure is as follows: (1) tally the detector count rates for 18 boron concentrations using the MCNP6 code; (2) select a fitting function which will be used; (3) get coefficients of that function by least square fitting; (4) obtain 18 boron concentrations from the fitting function with the known coefficients; (5) obtain the boron concentration error by

Table 1 – Boron meter geometry.

Component	Size (cm)
Boron meter radius	12.7
Boron meter height	55
BF_3 detector radius	1.588
Neutron source radius	2.0
Stainless steel thickness	0.317

Table 2 – Boron meter material.

Material	Density (g/cm^3)
BF_3 gas	2.567×10^{-3}
Stainless steel	8.03
H_2O w/o boron	0.69

subtracting the reference boron concentration from the calculated boron concentration; and (6) a root-mean-square (RMS) error is calculated from the 18 boron concentration errors. In this work, the 18 points are 0, 10, 50, 100, 250, 500, 750, 1,000, 1,250, 1,500, 1,750, 2,000, 2,250, 2,500, 2,750, 3,000, 4,000, and 5,000 ppm. The procedure is summarized in Fig. 4.

3.2. *Fitting functions*

3.2.1. *Boronline equation*

The Boronline equation which Pirat suggested [13], shown in Eq. (4), has been used for commercial boron meters in PWRs.

$$\text{Count rate} = \frac{1}{a \times C_b^2 + b \times C_b + c}, \quad (4)$$

where C_b is the boron concentration and a, b, and c are the coefficients of this equation.

3.2.2. *Exponential equation*

Eq. (5) shows the exponential equation.

$$\text{Count rate} = a \times \exp(-b \times C_b) + c, \quad (5)$$

where C_b is the boron concentration and a, b, and c are the coefficients of this equation.

3.2.3. *Rational functions*

Eq. (6) shows the rational functions.

$$\text{Count rate} = \frac{\sum_{i=0}^{n} a_i C_b^i}{1 + \sum_{j=1}^{m} b_j C_b^j}, \quad (6)$$

where C_b is the boron concentration and a_i and b_j, are the coefficients of this function. Eq. (6) is named *Rational-n-m*

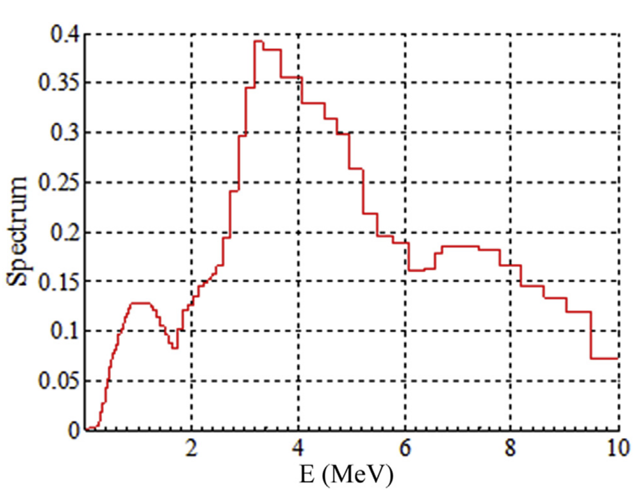

Fig. 2 – *Am-Be* neutron source spectrum.

because the numerator is the n^{th} order and the denominator is the m^{th} order. Therefore, the Boronline equation is also a rational function, *Rational-0-2*.

3.2.4. *Fitting function results*

The coefficients of several fitting functions were determined by least square fitting. Table 3 shows the coefficients, RMS error, and maximum error of 18 boron concentrations according to the fitting function.

In terms of the RMS error, we observe that the Exponential, Rational-2-0, and Rational-3-0 show larger errors, whereas the Rational-1-1, Rational-1-2, Rational-2-2, Rational-3-3, and Rational-0-3 show smaller errors than the Boronline equation. Especially, the Rational-0-3 and Rational-3-3 showed the lowest errors with just 0.73 ppm. Furthermore, it is shown that they provide the minimum values, i.e., 1.32 ppm, for the maximum error. Considering the degree of freedom, Rational-0-3, rather than Rational-3-3, will be adopted for performance evaluation of the multi-detector in Section 4.

4. Performance evaluation of multi-detector

4.1. *Concept of multi-detector*

However, a high-level sensitivity detector has a high detection efficiency for low level neutron flux. However, pulse pile-up phenomena can occur in such detectors. However, only using a low-level sensitivity detector makes it difficult to detect neutrons efficiently when the neutron flux is low. To solve this problem, a multi-detector composed of both a high-level and a low-level sensitivity detector was invented, as shown in Fig. 5.

The multi-detector is composed of four low-level sensitivity detectors with a BF_3 gas density of 2.567×10^{-3} g/cm^3 and two high-level sensitivity detectors with a BF_3 gas density of 5.134×10^{-4} g/cm^3 as in Fig. 5. Cases are divided according to the number of regions as follows: one-region, two-region, and three-region cases. The one-region case was introduced in Section 2. For the two-region case, only low-level sensitivity detectors are used in the 0–1,000 ppm range and both high-level and low-level detectors are used in the 1,000–5,000 ppm range, as shown in Fig. 6. The fitting function is applied separately for the two ranges.

For the three-region case, only low-level sensitivity detectors are used in the 0–1,000 ppm range, both high-level and low-level detectors are used in the 1,000–2,000 ppm range, and only high-level sensitivity detectors are used in the 2,000–5,000 ppm range, as shown in Fig. 7. The fitting function is applied separately for the three ranges.

Table 4 describes the boron concentration RMS error of the one-range, two-range, and three-range cases. In the three cases, the Rational-0-3 shows a smaller boron concentration error than the Boronline. Both Boronline and Rational-0-3 show that the boron concentration error decreases as the number of fitting ranges increase. We observe that the increase of accuracy of Boronline is more pronounced than that of Rational-0-3 because the accuracy of Rational-0-3 is already very good even in the one-range case.

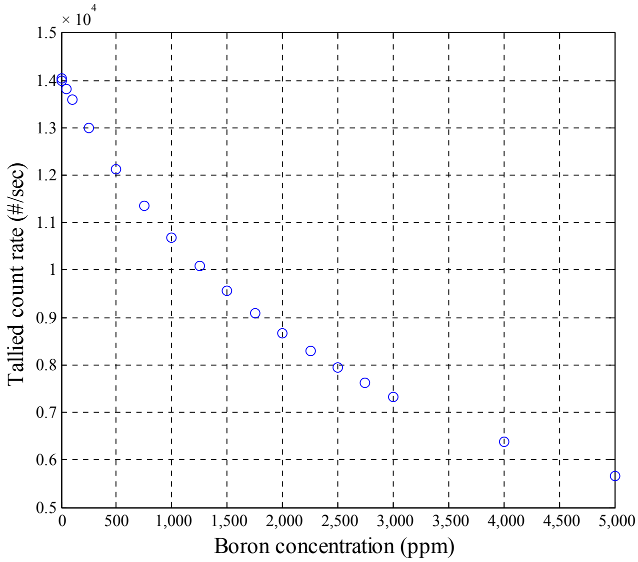

Fig. 3 – Tallied count rate according to boron concentration. ppm, parts per million.

4.2. *Description of noise contamination*

For field measurement data, there are noises in the detector count signals from boron meters. From a statistical point of view, the magnitude of noises is inversely proportional to the square root of detector count rate. In this research, the analyses have been performed under the assumption that the noise is inversely proportional to the count rate. This assumption means that the relative contribution to RMS error from the high boron concentration range will be weighted higher in order to increase accuracy at high boron concentrations. It was strategically chosen due to the fact that the measured data of the commercial boron meter shows higher errors in the high boron concentration range. In short, to reflect the uncertainty in the simulation from the field noise, the tallied count rate was contaminated with inversely proportional noises, as written in Eq. (7).

$$\text{Noise} = \frac{60,000}{\text{Count rate}} \times \xi; \quad 0 \le \xi = \text{Random number} \le 1. \tag{7}$$

Fig. 8 shows the noise in the one-range, two-range, and three-range cases. Analyses were performed 1,000 times, and the average and standard deviation of the 1,000 boron concentration RMS errors were calculated.

4.3. *Accuracy assessments of multi-detector with noise contamination*

Figs. 9 and 10 show the average boron concentration error with standard deviation at each boron concentration from the 1,000 time analyses.

It is shown in Fig. 9 and 10 that, as boron concentration increases, the average and standard deviation of boron concentration RMS errors increase. We observe that, as the number of fitting ranges increases, the boron concentration error and the corresponding standard deviation decrease, as shown in both figures. Also, it is noticeable that the boron

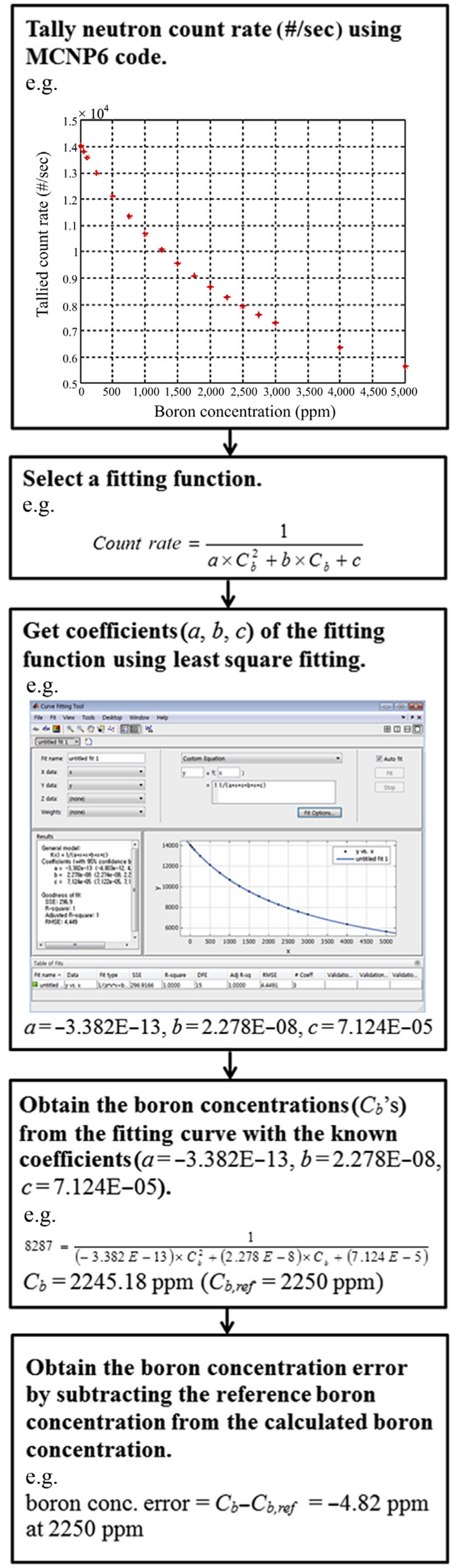

Fig. 4 – Fitting procedure.

Table 3 – Boron concentration error according to fitting functions.

Fitting function	Coefficients	Boron concentration RMS error (ppm)	Boron concentration maximum error (ppm)
Boronline	$a = -3.382 \times 10^{-13}$ $b = 2.278 \times 10^{-8}$ $c = 7.124 \times 10^{-5}$	3.30	7.32
Exponential	$a = 9.517 \times 10^{+3}$ $b = 4.241 \times 10^{-4}$ $c = 4.519 \times 10^{+3}$	61.44	149.73
Rational-2-0	$a_0 = 1.403 \times 10^{+4}$ $a_1 = -3.541$ $a_2 = 3.735 \times 10^{-4}$	214.51	670.20
Rational-3-0	$a_0 = 1.403 \times 10^{+4}$ $a_1 = -4.168$ $a_2 = 8.852 \times 10^{-4}$ $a_3 = -7.730 \times 10^{-8}$	62.96	245.40
Rational-1-1	$a_0 = 1.404 \times 10^{+4}$ $a_1 = 2.308 \times 10^{-1}$ $b_1 = 3.367 \times 10^{-4}$	2.27	5.05
Rational-1-2	$a_0 = 1.404 \times 10^{+4}$ $a_1 = 6.481 \times 10^{-1}$ $b_1 = 3.672 \times 10^{-4}$ $b_2 = 8.653 \times 10^{-9}$	0.75	1.36
Rational-2-2	$a_0 = 1.404 \times 10^{+4}$ $a_1 = 6.481 \times 10^{-1}$ $a_2 = -2.354 \times 10^{-10}$ $b_1 = 3.672 \times 10^{-4}$ $b_2 = 8.653 \times 10^{-9}$	0.74	1.37
Rational-3-3	$a_0 = 1.404 \times 10^{+4}$ $a_1 = -2.256 \times 10^{-6}$ $a_2 = 5.378 \times 10^{-10}$ $a_3 = 3.961 \times 10^{-14}$ $b_1 = 3.209 \times 10^{-4}$ $b_2 = -5.969 \times 10^{-9}$ $b_3 = 1.964 \times 10^{-13}$	0.73	1.32
Rational-0-3	$a_0 = 1.404 \times 10^{+4}$ $b_1 = 3.209 \times 10^{-4}$ $b_2 = -5.969 \times 10^{-9}$ $b_3 = 1.964 \times 10^{-13}$	0.73	1.32

ppm, parts per million; RMS, root-mean-square.

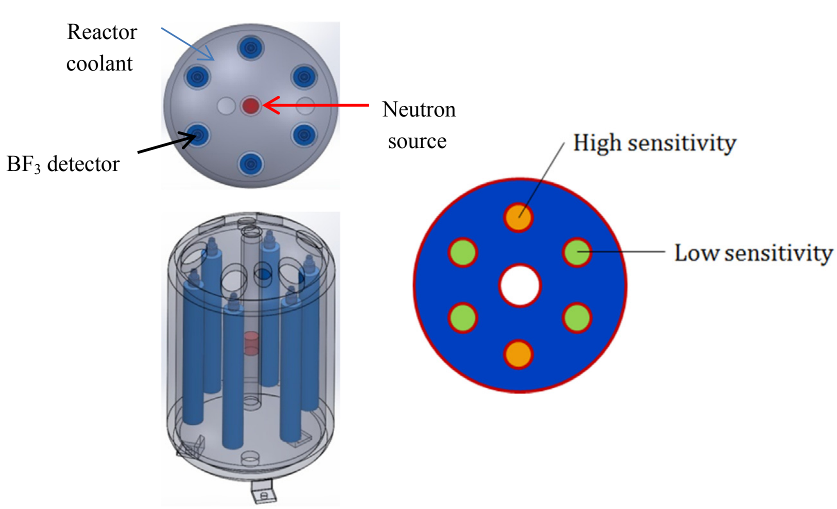

Fig. 5 – Multi-detector geometry.

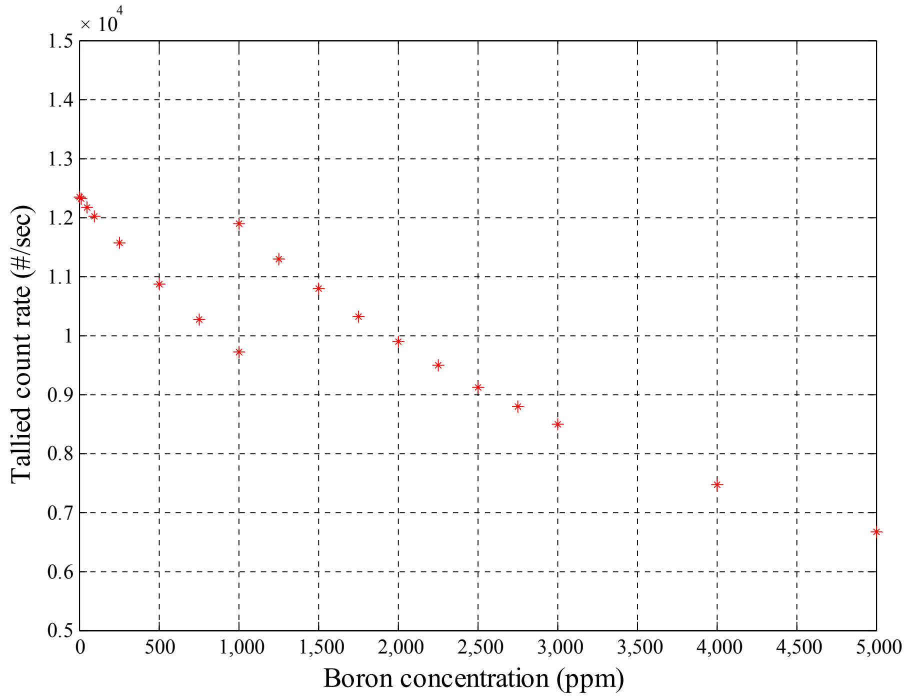

Fig. 6 – Tallied count rate in the two-region case.

concentration error of the Rational-0-3 is smaller than the one of the Boronline.

The average and standard deviation from 1,000 boron concentration RMS errors with noise contamination are summarized in Table 5.

We observe that the Rational-0-3 shows smaller error than the Boronline in all cases; one-range, two-range, and three-range cases. However, the standard deviations are at a similar level between the two functions in the same case. As the number in the fitting range increases, it is shown that not

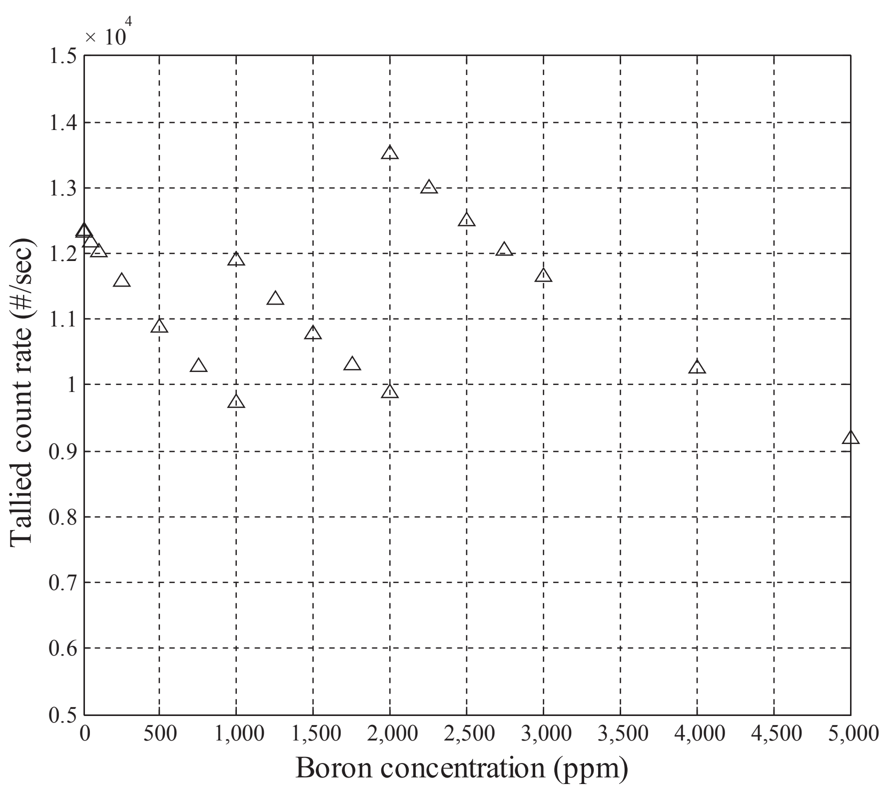

Fig. 7 – Tallied count rate in the three-region case.

Table 4 – Boron concentration error of one-range, two-range, and three-range cases.

Function	One-range (ppm)	Two-range (ppm)	Three-range (ppm)
Boronline	3.30	1.15	0.91
Rational-0-3	0.73	0.72	0.71

ppm, parts per million.

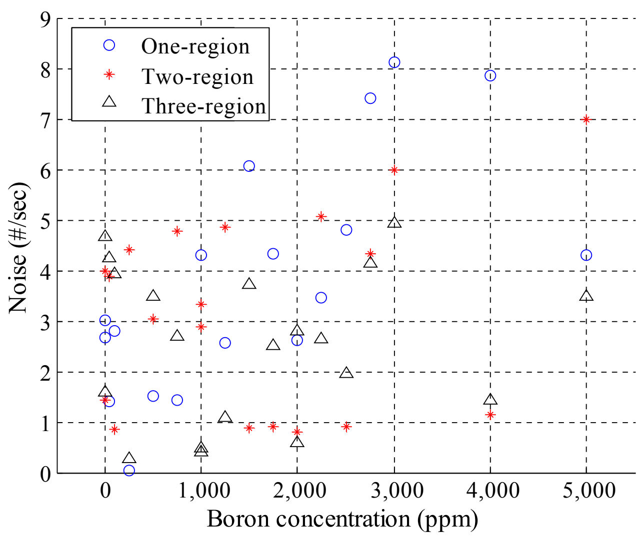

Fig. 8 – Noise in the one-region, two-region, and three-region cases. ppm, parts per million.

only the error, but also its standard deviation decreases. As a result, comparing the Boronline results in one-range with the Rational-0-3 results in three-range, we observe that the boron concentration error decreases from 5.95 ppm to 1.83 ppm and

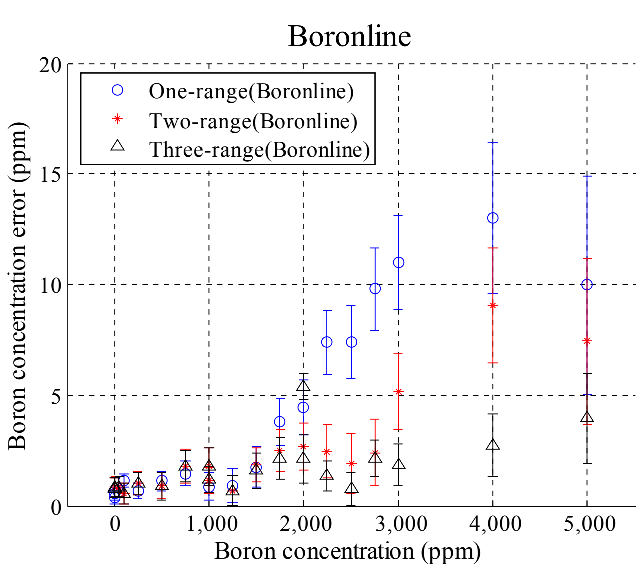

Fig. 9 – Boron concentration RMS error from 1,000 times analyses adopting the Boronline equation. ppm, parts per million; RMS, root mean square.

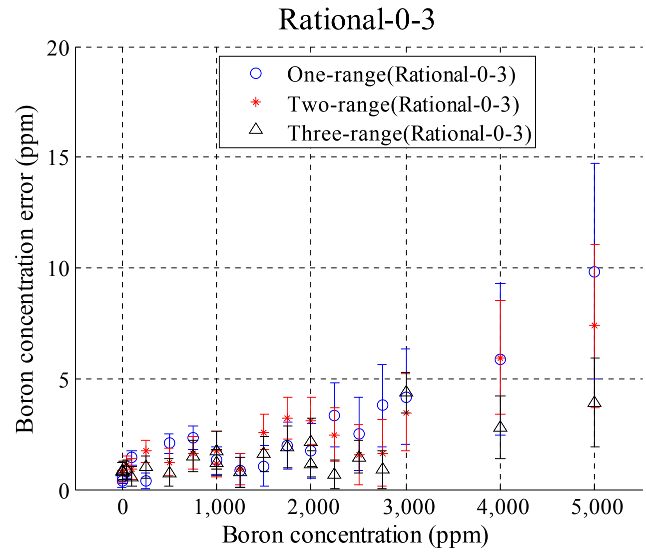

Fig. 10 – Boron concentration RMS error from 1,000 times analyses adopting the Rational-0-3 function. ppm, parts per million; RMS, root mean square.

the corresponding standard deviation also decreases from 0.64 ppm to 0.26 ppm. This result represents a reduction by a factor of 3 of the uncertainty measurement.

5. Conclusions

A new boron meter evaluation model was developed and two approaches were considered to improve the accuracy of boron meters: the first approach consists in adopting new fitting functions and the second approach consists in using a multi-detector composed of high-level and low-level sensitivity detectors. Among several fitting functions, the fitting function Rational-0-3 showed good results compared with the Boronline equation currently in use in commercial boron meters, with a boron concentration error of 0.73 ppm compared with Boronline's 3.30 ppm. As for the second approach, the count rate signals were contaminated with noise in order to replicate the field measurement data, and tested with a multi-detector 1,000 times. An average and the corresponding standard deviations were obtained from 1,000 boron concentration root-mean-square (RMS) errors. As a result, it was observed the Rational-0-3 showed smaller errors than the Boronline in the one-range, two-range, and three-range cases. However, the standard deviations were at a similar level between the two functions in the same case. Nevertheless, as

Table 5 – Boron concentration RMS error with noise contamination.

Function	One-range (ppm)	Two-range (ppm)	Three-range (ppm)
Boronline	5.95 ± 0.64	3.28 ± 0.58	2.07 ± 0.23
Rational-0-3	3.26 ± 0.79	2.81 ± 0.56	1.83 ± 0.26

ppm, parts per million; RMS, root mean square.

the number of fitting ranges increases, it was shown that not only the error, but also its standard deviation decreases. In summary, comparing the Boronline results in one-range with the Rational-0-3 results in three-range, it was observed that the boron concentration error decreased from 5.95 ppm to 1.83 ppm and the corresponding standard deviation also decreased from 0.64 ppm to 0.26 ppm. This result represents a reduction by a factor of 3 of the boron concentration error and its standard deviation.

In the near future, the new function, Rational-0-3, and the multi-detector will be applied to boron meters in test facilities to investigate feasibility of use in commercial nuclear power plants in Korea.

Conflicts of interest

All authors have no conflicts of interest to declare.

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