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Application of Rational Function for Accuracy Improvement of Boron Meter Model

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1. Introduction

In light water reactors (LWRs), soluble boric acid is added to the reactor coolant to compensate excess reactivity. In order to maintain the reactor core at the critical state, it is essential to adjust the amount of soluble boric acid because the excess reactivity gets decreased as the reactor core burns. It is highly recommended to continuously monitor the boron concentration in the reactor coolant.

For the measurement of boron concentration, two methods have been used: (1) a periodical chemical sampling method, and (2) continuous monitoring by a boron meter. As for the accuracy, it is known that chemical sampling shows higher accuracy (~0.2 %) than the boron meter (~2 %) [1]. However, chemical sampling is inappropriate for continuous monitoring due to its long process time, whereas the boron meter is available for continuous monitoring. Even though many boron meters have been used in nuclear power plants all over the world, there is still a strong need for accuracy improvement of the boron meter.

To improve accuracy of the boron meter, Lee et al. tried sensitivity tests for several boric acid thicknesses in one-dimension [2]. On the other hand, Pirat suggested a new boron meter whose accuracy was improved up to 1 % by using the rational form of fitting curve function [3]. Also, the exponential function was used to fit boron concentration by Lee [4]. In this study, more diverse fitting curves are tested to optimize the fitting curve to improve the accuracy of the boron meter.

2. Boron Meter Model

2.1 Model problem

The geometry and materials of the boron meter model are shown in Tables I and II, respectively. The boron meter is composed of a neutron source and detectors. The *Am-Be* neutron source is positioned at the center of the cylinder, and four detectors are placed around the source. They are surrounded by stainless steel 304 marked red lines as in Fig. 1.

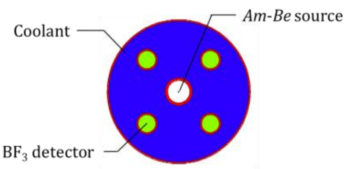

Fig. 1. Top view of the boron meter.

Table I. Geometry of Boron Meter

Structure	Size [cm]
Radius of boron meter	12.7
Height of boron meter	55
Radius of detector	1.588
Radius of source	2.0
Thickness of stainless steel	0.317

Table II. Materials of Boron Meter

Material	Density [g/cm^3]
BF_3 gas	2.567e-3
Stainless steel 304	8.03
H_2O without boron	0.69

2.2 Am-Be neutron source

Source neutrons are inserted continuously from the alpha decay of americium as in Eq. (1) and the (α,n) reaction of beryllium as in Eq. (2).

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

$$ {}^{9}_{4}Be + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + {}^{1}_{0}n. \quad (2)$$

The americium releases about 5.5 MeV alpha particles and the beryllium emits neutrons from (α,n) reactions [5]. Fig. 2 shows the *Am-Be* neutron source spectrum generated by TRITON and ORIGEN [6]. The amount of americium is one-tenth that of beryllium. TRITON homogenized the *Am-Be* compound and ORIGEN simulated the decay of the isotopes for one day.

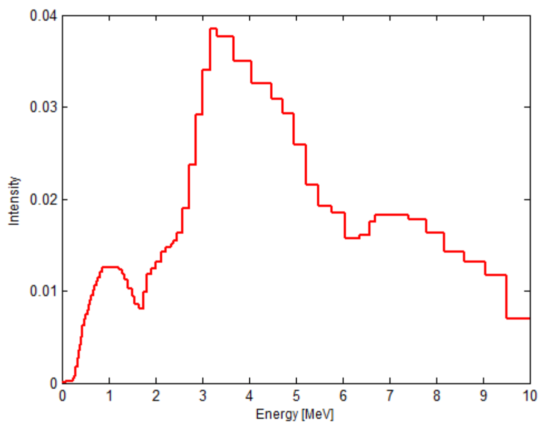

Fig. 2. *Am-Be* neutron source spectrum.

2.3 BF_3 detector

In general, BF_3 detectors are composed of BF_3 gas under 0.5-1.0 atmosphere pressure. The charged particles are emitted from the absorption reactions of ^{10}B.

$$^{10}_{4}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He. \qquad (3)$$

The ion pairs produced from the charged particles in Eq. (3) will be counted by the BF_3 detectors. MCNPX was used for (n,α) reaction modeling, and the number of absorption reactions, proportional to the detector signal, was tallied with the 'pulse height tally' option [7]. Table III shows the tallied count rates corresponding to boron concentrations. In this simulation, the efficiency of the detector is assumed to be 100 %.

Table III. Count Rates by MCNPX Simulation

Boron concentration [ppm]	Tallied count rate (#/source neutron)
10	0.02335 ± 0.00060
50	0.02305 ± 0.00070
100	0.02270 ± 0.00070
250	0.02169 ± 0.00070
500	0.02021 ± 0.00070
750	0.01893 ± 0.00070
1000	0.01780 ± 0.00070
1250	0.01681 ± 0.00080
1500	0.01594 ± 0.00080
1750	0.01517 ± 0.00080
2000	0.01447 ± 0.00080
2250	0.01383 ± 0.00150
2500	0.01326 ± 0.00090
2750	0.01273 ± 0.00090
3000	0.01224 ± 0.00090
4000	0.01063 ± 0.00310
5000	0.00944 ± 0.00320
6000	0.00848 ± 0.00340

3. Fitting Model

3.1 Fitting mechanism

The fitting mechanism is as follows: (1) tallying detector count rates about diverse boron concentrations in reactor coolant, (2) selecting the fitting curve, (3) getting the coefficients of the fitting curve from the tallied count rates by least square fitting, (4) obtaining a boron concentration from the completed fitting curve formulation (the coefficients were determined by least square fitting), (5) getting the boron concentration error by comparison with the reference boron concentration.

3.2 Boronline equation

The Boronline that has been used in nuclear power plants all over the world uses a three-term rational fitting equation that Pirat suggested like Eq. (4).

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

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

3.3 Exponential equation

The exponential equation used by Lee is like Eq. (5).

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

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

3.4 Rational function fitting

The rational functions are used like Eq. (6) [8].

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

where C_b is the boron concentration, and a_i and b_j are the coefficients of the equations. Here, the equations are denoted using the order of polynomials in the numerator and denominator equations. In other words, Eq. (6) is named *Rational-n-m* when the numerator is the *n*-th order and the denominator is the *m*-th order. For instance, the Boronline equation in Section 3.2 is *Rational-0-2*.

4. Numerical Results

The coefficients of the diverse fitting curve equations were determined by least square fitting. The count rates were obtained from these fitted equations. Fig. 3 shows the count rate of each fitting function.

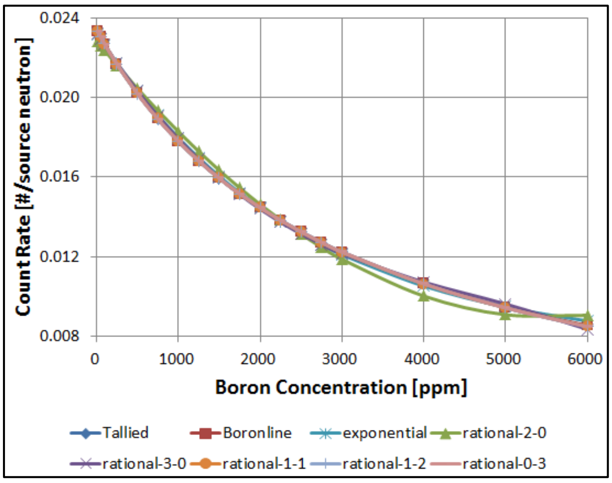

Fig. 3. Count rate of each equation.

Since the count rate errors of the Exponential, *Rational-2-0*, and *Rational-3-0* equations are much larger than that of the Boronline equation, Fig. 4 shows the count rate errors for only Boronline, *Rational-1-1*, *Rational-1-2*, and *Rational-0-3*. Here, the count rate error indicates the difference between fitted value in Fig. 3 and tallied value in Table III.

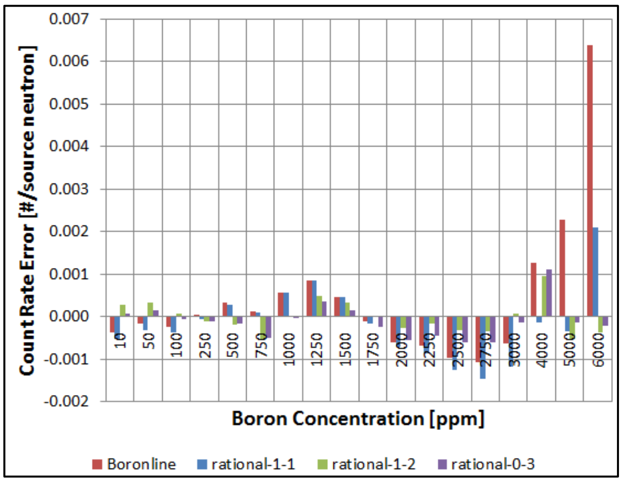

Fig. 4. Count rate errors of four equations.

The boron concentration was estimated from the equations with the determined coefficients. The boron concentration errors could be obtained from these estimated boron concentrations. Table IV describes the root-mean-square (RMS) of the boron concentration errors at 10, 50, 100, 250, 500, 750, 1000, 1250, 1500, 1750, 2000, 2250, 2500, 2750, 3000, 4000, 5000, and 6000 ppm.

Table IV. RMS of Boron Concentration Errors

Fitting equation	RMS error [ppm]
Boronline	16.98
Exponential	135.77
Rational-2-0	202.32
Rational-3-0	56.32
Rational-1-1	6.46
Rational-1-2	2.55
Rational-0-3	2.71

From Table IV, it is noted that the RMS error of the Exponential function, *Rational-2-0*, and *Rational-3-0* are larger than that of the Boronline equation. Fig. 5 shows the boron concentration errors of *Rational-1-1*, *Rational-1-2*, and *Rational-0-3*, which show much lower errors than the Boronline equation.

Both *Rational-1-2* and *Rational-0-3* show greater improvement of accuracy than the *Rational-1-1*. It is observed that *Rational-1-2* shows the lowest error at 2000-3000 ppm, whereas *Rational-0-3* shows the lowest error at 5000-6000 ppm. On the other hand, *Rational-1-2* shows the lowest error along the whole range of the boron concentration.

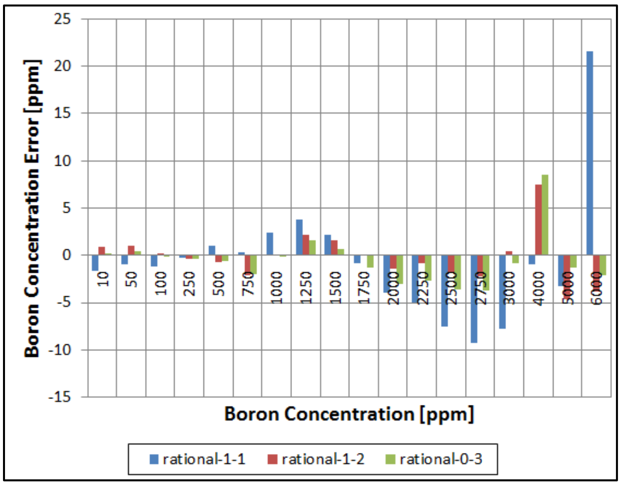

Fig. 5. Boron concentration errors of three equations.

5. Conclusions

Several boron meter fitting equations are tested to improve the accuracy of boron meters. The Boronline equation shows an RMS error of 16.98 ppm over 0-6000 ppm boron concentrations. The exponential, *Rational-2-0*, and *Rational-3-0* equations showed higher errors than Boronline. The *Rational-1-1*, *Rational-1-2*, and *Rational-0-3* equations showed lower errors than that of Boronline. Especially, both *Rational-1-2* and *Rational-0-3* showed great improvement of accuracy, with RMS errors less than 3 ppm. Thus, it is highly recommended to apply them to boron meters to improve accuracy.

Acknowledgements

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