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Original Article

Development of accuracy enhancement system for boron meters using multisensitive detector for reactor safety

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ABSTRACT

Boric acid is used as a coolant for pressurized-water reactors, and the degree of burnup is controlled by the concentration of boric acid. Therefore, accurate measurement of the concentration of boric acid is an important factor in reactor safety. An improved system was proposed for the accurate determination of boron concentration. A new boron-concentration measurement technique, called multisensitive detection, was developed to improve the measurement accuracy of boron meters. In previous studies, laboratory-scale experiments were performed based on different sensitivity detectors, confirming a 65% better accuracy than conventional single-detector boron meters. Based on these experimental results, an experimental system simulating the coolant-circulation environment in the reactor was constructed; accuracy analysis of the boron meter with a multisensitivity detector was performed at the actual coolant pressure and temperature. In this study, the boron concentration conversion equation was derived from the calibration test, and the accuracy of the boron concentration conversion equation was examined through a repeatability test. Through the experiment, it was confirmed that the accuracy was up to 87.5% higher than the conventional single-detector boron meter.

1. Introduction

Boric acid water is used as a nuclear reactor coolant and is added to control the reactivity in pressurized-water reactors (PWRs) operating in Korea [1]. Since the degree of burnup depends on the concentration of boric acid, precise measurement of the boric acid concentration of the coolant is essential for reactor operation safety [2]. Two main techniques for measuring boron concentration are used. The boron meter is used only to observe changes in boric acid concentration due to high measurement errors (of the order of 2%). On the other hand, chemical analysis is mainly used for boric acid concentration measurement due to low measurement error (of the order of 0.2%) [3–5]. However, in the case of boron meters, there is an advantage that the concentration of the coolant can be measured in real time as opposed to chemical analysis that can be performed once a day [6]. Therefore, the operation safety of reactors can be significantly improved by enhancing the accuracy of boron meters used for real-time measurements. In addition, because boron concentration measurement does not generate waste, semi-permanent operation is performed, which improves reactor operation stability. To improve accuracy, which is a disadvantage of boron meters, design and simulation of a boron meter incorporating the concept of a multisensitivity detector were performed [7–10]; an experiment was conducted to analyse the accuracy of the multisensitivity detector based on the simulation results. At low concentrations, a high neutron flux is measured using a low-sensitivity detector, and at high concentrations, a low neutron flux is measured using a high-sensitivity detector to obtain the stable count rate in the entire boron concentration interval to prevent overlap and saturation [11,12]. Experimental results confirmed that the accuracy was improved by approximately 50% compared with the boron meter using the conventional single-sensitivity detector [13]. However, previous studies were performed on a laboratory scale, and no accuracy analysis has been performed in an actual cooling water circulation environment [14]. Therefore, in this study, a boron meter with improved accuracy was experimentally evaluated in a water circulation environment built on actual reactor environment.

2. Experimental set-up

2.1. Neutron source

An Am–Be neutron source with an activity of 1 Ci (3.7×10^{10}

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Bq), an N20-capsule product from Ekert & Ziegler, was used to analyse the accuracy of the boron meter based on the coolant-circulation environment in an actual reactor. The height and diameter of the neutron source were 4.86 cm and 1.91 cm, respectively. As the half-life of Am-241 is 432 years, which is much longer than the lifespan of human beings, no reduction in the radioactivity due to radioactive decay with time was considered. It is suitable for boron meters installed inside the reactor coolant pipe and used semi-permanently. The neutron emission rate of this source is $2.2 \times 10^6 \frac{n}{s}$.

2.2. Detector

Commercially available detectors were selected with their size and sensitivity based on the simulation; the specifications of the detectors are given in Table 1. Sensitivity values of 11.3 cps/nv and 28 cps/nv were used for the low-sensitivity detector (LND 20292) and high-sensitivity detectors (LND 2528), respectively. The diameter of the two detectors was 2.54 cm, and their heights were 39.0 and 28.8 cm, respectively.

2.3. Experimental setup and method

To maintain the pressure and temperature encountered in an actual reactor environment, a boric acid water pressure vessel was constructed. Table 2 lists the structural specifications. Fig. 1 shows the schematic of the pressure vessel and sample assembly. Fig. 2 shows the fabricated pressure vessel and sample assembly. Based on previous experiments confirming improvements in accuracy, the distance between the source and detector, which could have a significant effect on the count-rate efficiency, was set to 81 mm. The pressure vessel was fabricated using stainless steel 304, which can withstand a maximum pressure of 13.8 bar to allow installation and operation regardless of the changes in pressure and temperature in an actual reactor environment [15]. The depth of the inlet hole was fixed such that the source could be inserted into the centre of the pressure vessel. The depth of the inlet of the detector was designed so that the effective height of the detector could be fully inserted, and the source was located at the centre of the active gas. A total of six detector inlet holes were located at the same distance from the source. BF_3 detectors, used as a low-sensitivity detector, were inserted into four holes, and ^3He detectors, used as high-sensitivity detectors, were inserted into the other two holes. The entire boric acid water circulation system is shown in Fig. 3. When the boric acid water with the target boric acid concentration was inserted into the water box, it was heated to the experimental temperature using the heater. Boric acid water was injected into the pressure vessel through the pump connected to the water box; the internal temperature was measured using the thermocouple installed in the pressure vessel. Boric acid water for the experiment was prepared by adding the amount of boric acid required for each ppm point to distilled water. The concentration was balanced in the entire boric acid circulation system by heating and circulation through the pump. Calibration tests for deriving the boron concentration conversion equation and repeatability tests for accuracy analysis of the conversion equation were performed. In the calibration test, boric acid water with 18 different concentrations of 0, 10, 50, 100, 250, 500, 750, 1000, 1250, 1500, 1750, 2000, 2250, 2500, 2750, 3000, 4000, and 5000 ppm was used. The accuracy of the boron concentration conversion equation for six different concentrations of boric acid water, 100, 500, 1000, 1500, 2000, and 3000 ppm was analysed in the repeatability test.

Table 2
Specification of the sample assembly and pressure vessel.

Structure	Thickness or Length
Pressure Vessel Length	51.2
Pressure Vessel Diameter	23.0
Detector Inserted Length	40.5
Detector Inserted Diameter	4.83
Am–Be Neutron Source Inserted Length	25.5
Am–Be Neutron Source Inserted Diameter	3.30
Shielding Assembly Length	92.1
Shielding Assembly Diameter	31.7

3. Result and discussion

3.1. Calibration test

The detector and neutron source were inserted into the pressure vessel, and boric acid water with 18 different concentrations was prepared and injected into the water box. It was heated to a temperature of 49 °C after insertion and circulated in the system for 1 h using a three-phase upper pump. After confirming that the temperature equilibrium is maintained in the entire system by checking the internal temperature of the pressure vessel and temperature of the water box, the valves installed in the outlet pipe were closed to maintain the pressure inside the vessel at 4.1 bar, which is the coolant-circulation pressure in reactors. The count rate was measured five times for 100 s at each boron concentration using four BF_3 detectors in the low-concentration range of 0–1500 ppm and using four BF_3 detectors and two ^3He detectors in the high-concentration range of 1500–5000 ppm. Before the experiment, the neutron source was removed, and the background count rate was measured to confirm that there was no effect of natural radiation. Table 3 and Fig. 4 present the average values of the count rate measured in the range of 0–5000 ppm and its standard deviations, according to the change in boron concentration at a temperature and pressure of 49 °C and 4.1 bar, respectively. The count rate decreased with the increasing concentration of boric acid, and the regression line was derived using the polynomial fitting curve. The relative standard deviation of the measurement of the count rates ranged from 20 to 50 cps in the entire circulation system, which indicated that the measured count rate was stable when using the high-sensitivity detector. The boron concentration conversion equation was derived using the measured values. Measurements and concentrations of boric acid were assigned to curve-fitting equations such as Equation (1), and coefficients were calculated using the least-square fitting method implemented using MATLAB.

$$\text{Rational} - 0 - 4\ \text{Equation}: \mathrm{P} = \frac{1}{A_{\perp}X^4 + A_2X^3 + A_3X^2 + A_4X + A_5} \qquad (1)$$

Table 1
Specification of the detectors.

Model	Sensitivity [cps/nv]	Gas density $[g/cm^3]$	Diameter [mm]	Length [mm]	Pressure [atm]
LND 20292	11.3	0.013954	25.4	390.5	0.921
LND 2528	28.0	0.000151	25.4	288.0	0.921

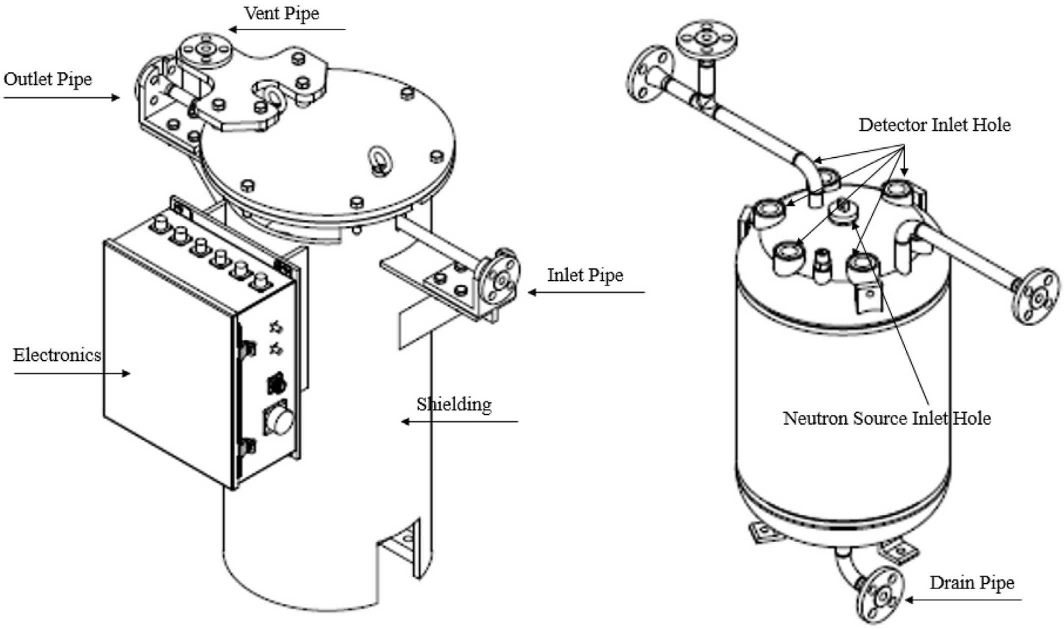

Fig. 1. Schematic of sample assembly (left) and pressure vessel (right).

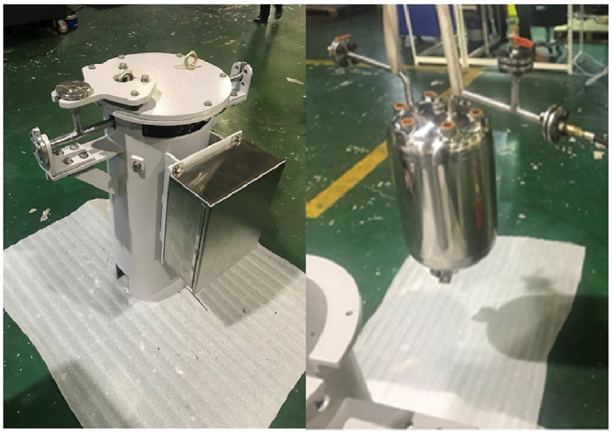

Fig. 2. Image of sample assembly (left) and pressure vessel (right).

Equation (1) is rational because the numerator is of the nth order and the denominator is of the mth order. The A_{series} coefficients of the rational equation were calculated [16]. Substituting the calculated coefficient into the rational equation, a boron concentration conversion equation was generated. By substituting the measured count rate value P in the generated boron concentration conversion equation, the boron concentration X could be calculated. For more accurate calibration, boron concentration values were determined by chemical analysis in the quality certification laboratory. The derived boron concentration conversion equation (rational-0-4) and measured values are shown in Fig. 5, and the calculated coefficients are listed in Table 4. In Fig. 5, the correlation coefficient (R^2) of the fitting curve, 0.9989, reflects the agreement with the measured count rate. It indicates that the accuracy of the boron concentration conversion equation derived from rational-0-4 is high. Table 5 presents the errors between the boron concentration measured via chemical analysis and that calculated using

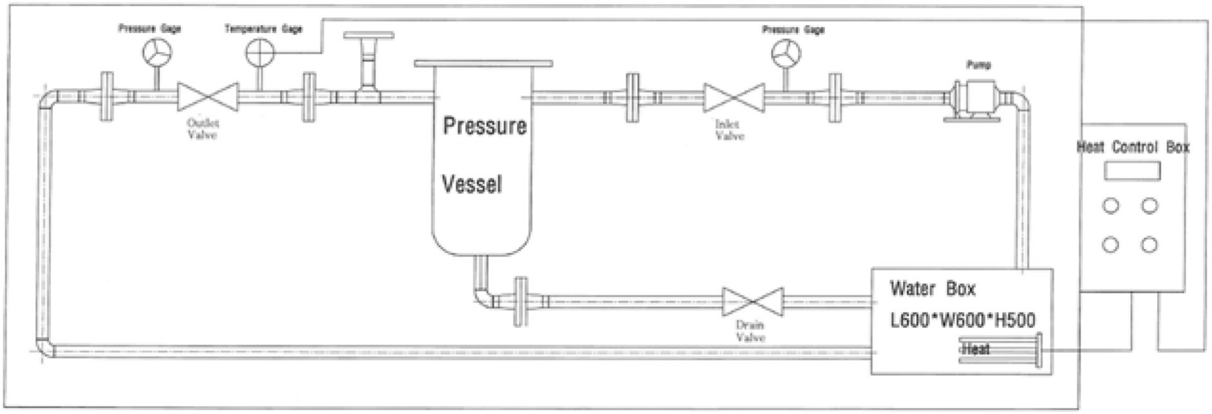

Fig. 3. Boric acid water circulation system.

Table 3
Measurement of the count rate of detectors in 0–5000 ppm.

Nominal Boron Concentration [ppm]	Count Rate Measurement [cps]	Standard Deviation [cps]	Temperature [°C]	Boric Acid Water Pressure
0	30880	23	48.307	4.1 bar
10	30692	21	49.289	4.1 bar
50	29582	26	49.259	4.1 bar
100	28547	30	49.321	4.1 bar
250	25846	24	49.072	4.1 bar
500	22706	24	48.865	4.1 bar
750	20349	21	48.823	4.1 bar
1000	18819	44	49.683	4.1 bar
1250	17293	43	48.994	4.1 bar
1500	16270	32	48.989	4.1 bar
1500	35473	34	48.856	4.1 bar
1750	33393	42	49.191	4.1 bar
2000	31806	23	49.035	4.1 bar
2250	30203	19	48.979	4.1 bar
2500	28701	33	49.269	4.1 bar
2750	27409	45	49.005	4.1 bar
3000	26671	56	49.072	4.1 bar
4000	23394	74	48.99	4.1 bar
5000	21578	65	48.975	4.1 bar

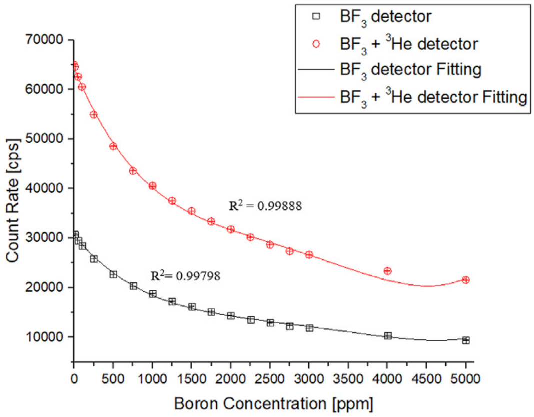

Fig. 4. Count rate measurement value according to boron concentration [0–5000 ppm].

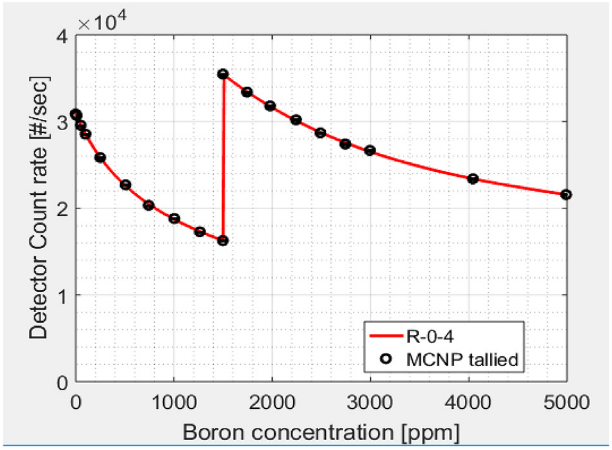

Fig. 5. Rational-0-4 fitting curve on measured count rate.

the boron concentration conversion equation. The average absolute error value in the range of the 0–5000 ppm total boron concentration was calculated as 12.457 ppm. The error rate obtained was 0.249%. This value is significantly lower than the error rate of the conventional single-detector boron meter (2%).

Table 4
Calculated coefficients of rational-0-4 equation.

Coefficient	0–1500 ppm Region	1500–5000 ppm Region
A_1	−5.42813E-18	−7.45337E-20
A_2	1.75190E-14	9.12064E-16
A_3	−2.06104E-11	−4.34490E-12
A_4	3.04461E-08	1.47705E-08
A_5	3.23382E-05	1.39521E-05

3.2. *Repeatability test*

To confirm the accuracy of the boron concentration conversion equation derived from the calibration test, the measured and calculated values of the count rate were checked by substituting the count rate value measured repeatedly at six boron concentrations. The test procedure was the same as the calibration test; the measurement was conducted five times for 100 s at each boron concentration point. The concentrations of boric acid measured via chemical analysis and those calculated using the boron concentration conversion equation are given in Table 6. The graphs showing the tendency of the results are shown in Fig. 6. The average of the errors in the measured values and that of the values obtained using the boron concentration conversion equation was calculated as 34.0855 ppm, and the error rate in the range of 0–5000 ppm was calculated as 0.68171%. The error rate in the repeatability test is higher than that in the calibration test. This is because the duration of the experiment exceeded the fatigue life and life expectancy of the BF_3 ($<10^8$ counts) detector. As the boron meter is semi-permanently operated after installation in the coolant system, this problem can be solved using ^{3}He detectors, which have the advantage of a high life expectancy ($<10^{12}$ counts) [17]. It shows low error (order of the 0.68%) compared to single-detector boron meter (order of the 2%). The multisensitivity boron meter shows low error close to that of chemical analysis with an error of 0.2% and real-time boron concentration measurement is possible. As a result, the stability of the reactor operation is expected to be greatly improved since the boron concentration of the coolant can be measured in real time using a multisensitivity boron meter.

4. Conclusion

Experiments were conducted to analyse the accuracy enhanced boron meter system with a multisensitivity detector using an

Table 5
Measured and calculated boron concentration and error [calibration test].

Nominal Boron Concentration [ppm]	Measured Boron Concentration [ppm]	Calculated Boron Concentration [ppm]	Boron Concentration Error [ppm]
0	0.03	1.49	1.46
10	9.5	8.05	−1.45
50	49	49.76	0.76
100	96	93.92	−2.08
250	237	240.36	3.36
500	497	489.26	−7.74
750	731	744.47	13.47
1000	957	943.92	−13.08
1250	1173	1180	7.00
1500	1382	1380.3	−1.70
1500	1382	1380.39	−1.61
1750	1623	1635.86	12.86
2000	1909	1871.39	−37.61
2250	2117	2152.26	35.26
2500	2487	2459.95	−27.05
2750	2721	2762.35	41.35
3000	2977	2951.91	−25.09
4000	3984	3987.01	3.01
5000	4901	4900.24	−0.76

Table 6
Measured and calculated boron concentration and error [repeatability test].

Nominal Boron Concentration [ppm]	Measured Boron Concentration [ppm]	Calculated Boron Concentration [ppm]	Boron Concentration Error [ppm]
100	98.212	105.075	6.863
500	488.865	490.27	1.405
1000	933.04	944.806	11.766
1500	1418.22	1338.5	−79.72
1500	1418.22	1341.71	−76.51
2000	1903.19	1892.16	−11.03
3000	2825.79	2887.57	61.78
4000	3753.5	3777.11	23.61

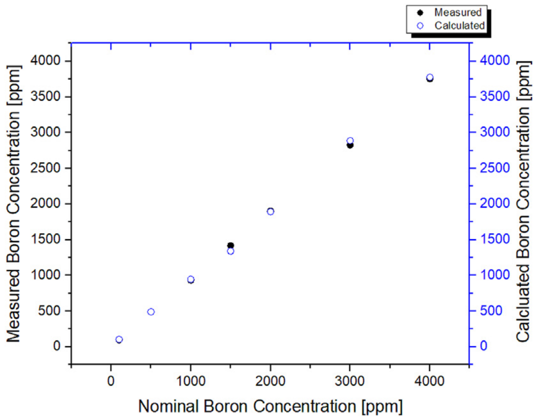

Fig. 6. Comparison of the measured value and calculated vale [repeatability test].

experimental system based on the coolant-circulation environment in an actual reactor. First, a calibration test was performed to derive the boron concentration conversion equation. The boron concentrations calculated using the boron concentration conversion equation derived from this test were compared with the measured values, and the error rate in the range of 0–5000 ppm was determined. The results showed that the accuracy of the boron meter with the multisensitivity detector was improved by 87.5% compared with that of the conventional single-sensitivity detector. Second, a repeatability test was performed to repeatedly confirm the accuracy of the boron concentration conversion equation. The accuracy obtained in the repeatability test was 65.9%, which is higher than the accuracy of the boron concentration conversion equation based on the calibration test results. The is attributed to the change in the count rate measured in the calibration test due to the fatigue of the BF_3 detector owing to continuous experiments. This problem can be solved using a ^{3}He detector with a long lifetime. This experimental study verified that the accuracy of the new boron meter was enhanced, and it would contribute significantly to the stability of reactor operations.

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Nomenclature

P	Count Rate [cps]
$A_1 - A_4$	Coefficients
X	Boron Concentration [ppm]
R_2	Coefficient of Determination

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2019.08.004.

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