CONTINUOUS MEASUREMENT OF BORON CONCENTRATION IN NUCLEAR POWER PLANTS: WHY IS IT ESSENTIAL FOR SAFE AND EFFICIENT OPERATION?

Miriam JIMENEZ and Patrick PIRAT
Rolls-Royce
23 chemin Vieux Chêne, 38240 Meylan, France
miriam.jimenez.cn@rolls-royce.com; patrick.pirat.cn@rolls-royce.com

ABSTRACT

As a neutron-absorber, Boron 10 plays a significant role in nuclear power plants as it is used in order to control reactivity in the core, together with control rods. For that reason; it is a key parameter that has to be controlled. In a similar way, it is crucial to be able to detect a boron dilution in the primary circuit, as it would causes severe damages if not detected and controlled. Thus, it comes as evidence that a boron concentration monitoring system is a key for every nuclear power plant.

Consequently, it becomes important to provide plant operators with a boron concentration measurement issued by a reliable, redundant, classified and qualified system, with high accuracy and short response time.

In order to cover this need, Rolls-Royce has designed Boronline®, the latest generation of boron meter, which provides nuclear power plant operators with a permanent record of boron concentration of primary circuit by way of continuous sampling and real-time measurements.

Boronline takes part of a new generation of Advanced Sensors and Measurements Technologies. In this paper, boron meter role, main functions and measuring principles will be detailed, as well as technical characteristics of the new generation of boronmeter will be presented.

Key Words: *boron concentration; accuracy; response time.*

1 INTRODUCTION

As a neutron-absorbing material, Boron is used in both PWR and BWR reactors for chemical control of neutron flux in primary circuit. Particularly, Boric acid is dissolved in the reactor coolant of nuclear power plants, so that Boron 10 absorbs thermal-neutron in order to compensate an excess of reactivity of reactor core. For that reason, Boron is recognized as taking part in the safety function of maintaining the reactor subcritical. Therefore, it is essential to be able to continuously measure boron concentration of primary circuit.

Moreover, in the event of an Inadvertent Boron Dilution, detecting it and alerting the operator becomes a crucial issue. Indeed, if an uncontrolled Boron dilution occurs (due to human error or equipment fail such as leakage) the unwanted reactivity introduced would lead to an incident if not detected and controlled sufficiently early. Consequently, equipping nuclear power plants with an in-line specific instrument for the measurement of boron concentration is a key aspect to ensure safe and efficient operation. A boron meter is a measuring device whose principal functions are: to provide real-time Boron concentration of the fluid flowing through it; and, in the event of an Inadvertent Boron Dilution, to detect it and to alert the operator by triggering a Dilution alarm.

The present paper describes design and functions of Boronline, the new generation of boron meters designed by Rolls-Royce. This paper has been divided into five parts. This introduction establishes the context and provides an overview of the report structure. The second chapter will examine the measuring principle of a boron meter, and the greatest challenges of its design. The third chapter presents Boronline system architecture. Chapter four analyzes the performances accomplished by Boronline and focuses on its highlights. The last section summarizes the content of this paper.

2 MEASURING PRINCIPLE

As it was pointed out in the introduction to this paper, Boron 10 has a large thermal-neutron cross-section. Boron meter principles are based on neutron absorption properties of Boron 10. Boron meter consists of a tank* through which the fluid to be analyzed flows. A sampling system ensures the fluid continuously flows through it. A neutron source irradiates the fluid (Fig.1). Because of its high cross-section for neutron capture, boron dissolved in the fluid absorbs some fraction of neutron. Remaining neutron reach the detector, causing a reaction in the chamber which produces a pulse of current. These pulses are detected and converted to a pulse count rate. Boron concentration and counting rate are related by a mathematical law (1). There is a negative correlation between counting rate and Boron concentration (Fig.2).

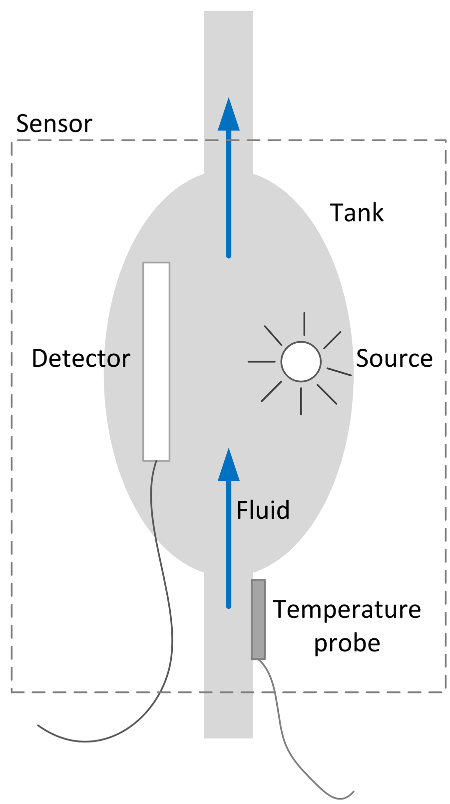

Figure 1: Measuring principle of a boron meter

* In this section, only the term "tank" is used, in order to keep the explanation of the measuring principle clear. Nonetheless, there are 2 versions of boron meter, one consisting of a tank, the other one consisting of an on-pipe device. Both are described in section 3. Throughout this paper, the term 'sensor' is used to refer to these four elements together (tank or pipe, detector, source and temperature probe).

$$C_r = \frac{1}{A.C_B^2 + B.C_B + C} \tag{1}$$

C_r: *Counting rate*
C_B: *Boron Concentration*
A, B, C: *calibration parameters*

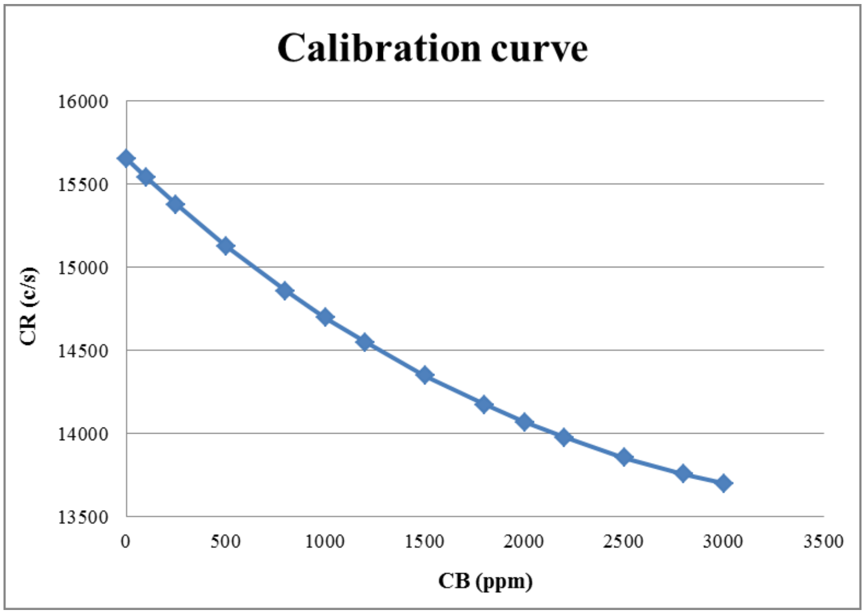

Figure 2: Calibration curve, or the negative correlation between counting rate and Boron concentration

It is well known that neutron emission obeys Poisson statistics. In other words, boron meter operating principle is based on a statistical phenomenon. As a result, signal delivered by the detector involves considerably great intrinsic fluctuation. Fig.3 illustrates this point clearly. The graph presents an example of recorded boron meter counting rate. These data were recorded in a period of 24H, while the system was working in on-site conditions, with boron concentration remaining stable. In this example, counting rate intrinsic fluctuation (standard deviation) is nearly 15%.

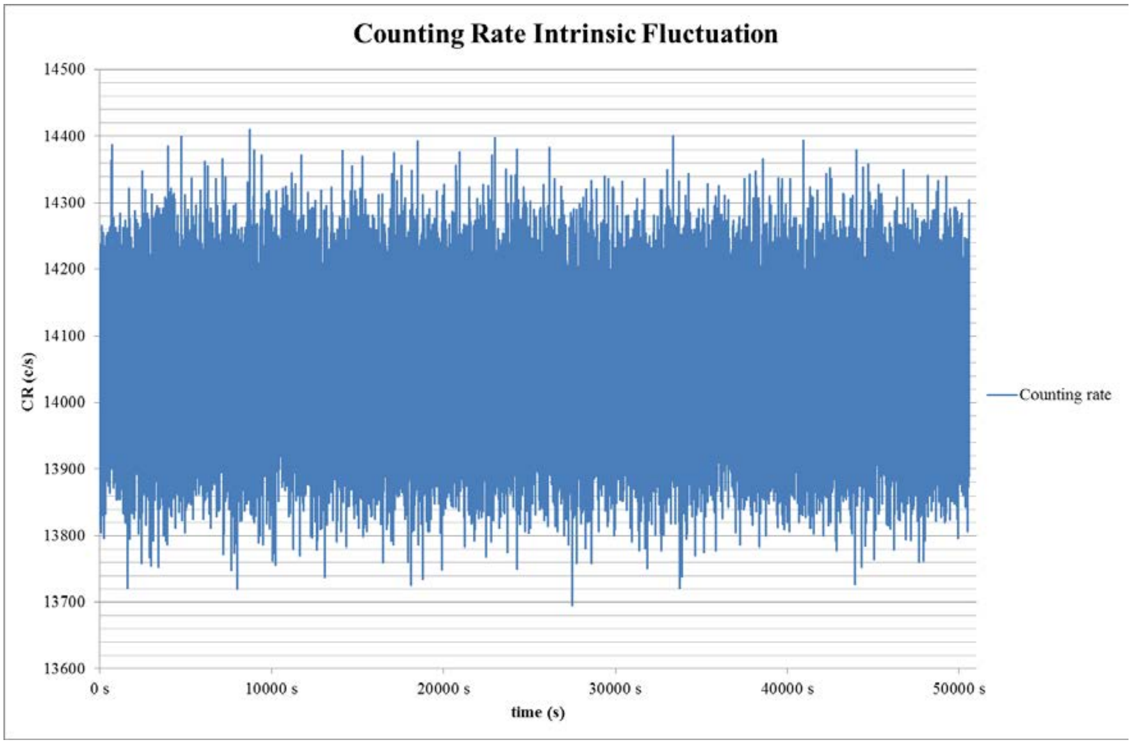

Figure 3: Counting rate intrinsic fluctuation (24H data recording)

As can be seen from the graph above, one of the main obstacles in the design of a boronmeter is dealing with intrinsic fluctuation. Certainly, one of the greatest challenges is to conceive a system that is able to reduce signal fluctuation as low as possible. This is one of the keys to provide a precise, stable measure of boron concentration.

Another important factor regarding boron meter design is response time. There is a negative correlation between response time and precision. Integrating a fluctuating signal over longer periods of time has been demonstrated to be a way to obtain more stable output signal; however, this method increases proportionally response time. Achieving the best compromise between precision and response time becomes then a primary concern of boron meter design. That is, reaching accurate signal while keeping response time as low as possible.

In summary, the most important factor concerning boron meter design is reducing intrinsic fluctuation in order to enhance accuracy, while keeping optimal response time. Both improvements combined allow ameliorating the compromise between accuracy and response time.

3 BORONLINE: SYSTEM ARCHITECTURE

Having discussed what a boron meter is and what its main functions are, the following is a brief description of how Boronline works and what its principal characteristics are.

As described in the previous chapter, boron meter consists of a sensor, holding a neutron detector and a neutron source. Pulse signal provided by the detector is transmitted to a rack containing two boards: a conditioning board, whose main function is shaping the pulse signal; and a processing board, which calculates boron concentration by solving the equation indicated previously. Besides, a temperature probe provides fluid temperature signal to the rack, so the measure of boron concentration is compensated regarding temperature effects. (Fig.4).

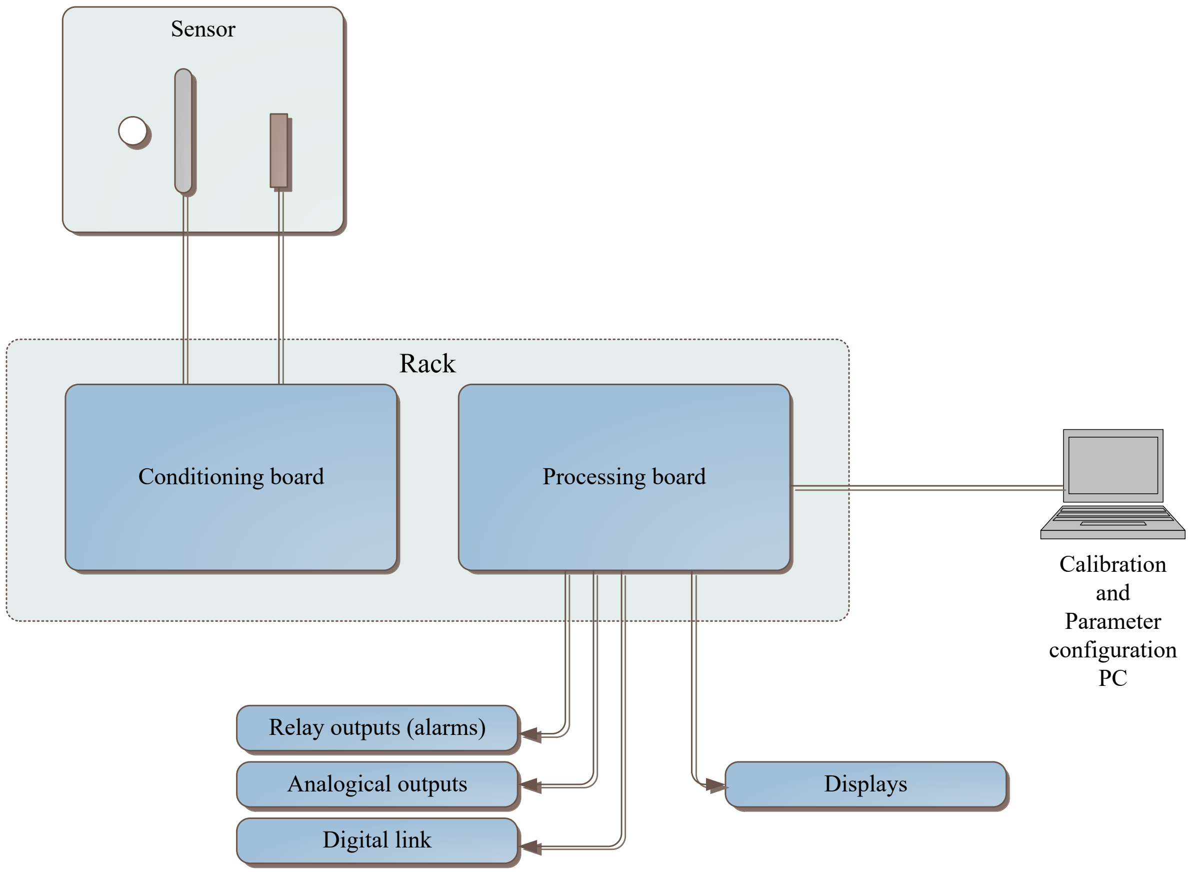

Figure 4: Boronline architecture

Processing board controls all inputs and outputs of the system. The most important outputs are: Boron concentration, which is provided by analogical output and on displays; and Dilution alarm, which is a relay output. As explained earlier, this alarm plays the vital role of alerting the operator in case of an Inadvertent Boron Dilution occurs, that is, when current Boron concentration measure crosses a defined threshold.

All the information resulting from processing board calculations is broadcasted to the Plant Computer by a digital output. A laptop including dedicated software is used to parameter the system. The main strength of Boronline is the filtering algorithm embedded in the processing board. The role of this algorithm, based on a recursive filter developed by Rolls-Royce, is flattening intrinsic fluctuation so that Boron concentration output is stable. Moreover, the filter lets the system follow signal long-term trend without inducing additional response time. The following section of this paper moves on to describe in greater detail the performances achieved thanks to the filtering algorithm.

With regard to sensor, there are two different kinds:

- Intrusive sensor, which consists of a tank. It needs a sampling system upstream, so the target fluid is bypassed.

• Non-intrusive sensor, which consists of an on-pipe device. It is directly mounted on the pipe through which the fluid to be analyzed flows. Main advantage of this version is that there is no need to bypass concerned pipe.

Both sensors are fully compatible with electronic rack, displays and laptop, as the detector signal is essentially identical for the two of them.

4 BORONLINE: ASSETS AND PERFORMANCES

As explained in the introduction, the most challenging aspect of designing and developing a boron meter is to provide a precise Boron concentration measurement while keeping reasonable response time. This section examines Boronline performances regarding these two characteristics.

The term “precision” is used here to refer to the standard deviation of measurement compared to the true value of CB (unknown). The terms “accuracy” and “precision” are here used interchangeably. “Response time”, can be defined as the period of time between the moment the real value of Boron concentration crosses the threshold and the moment the Dilution alarm is triggered.

As far as accuracy is concerned, key influencing factors can be listed as follows:

- intrinsic fluctuation,
- calibration of the system,
- electronics drift,
- temperature,
- Neutron source decay

Due to practical constraints, this paper cannot provide a comprehensive review of each of these factors. It will examine mainly intrinsic fluctuation; as it is the predominant one. Nevertheless, it is important to mention that Boronline embedded software includes correction for deviation due to calibration, electronics drift and temperature effects. Certainly, Boronline processing board includes a Rolls-Royce software application allowing every factor of deviation to be treated and optimized. As a result, performances in terms of accuracy are remarkably enhanced. Fig. 5 is a good example of this improvement. The green graph shows non filtered boron concentration at 1800ppm, resulting from just converting counting rate presented in section 2. The results obtained from converting then filtering this same counting rate are shown in the red graph below. Thanks to Boronline filtering algorithm, standard deviation is reduced to 1.2% in this example. The utility of the filter is thus proved. On average, accuracy of Boronline non-intrusive sensor is approximately 1.5% of the measured value, all influencing factors included.

Turning now to response time, in the traditional approach, old boron meter technologies resolved the fluctuation problem by integrating the detector signal over a significantly long period of time. As a result, the response time was proportionally augmented. In terms of safety, this is a considerable disadvantage, as it is crucial to minimize the time the system takes to trigger the Dilution alarm. Boronline filter allows the system to follow signal trend in order not to introduce extra delay. Thus, the response time is optimized. A good illustration of the performances of the system regarding response time is provided in Fig.6. The graph shows the response time of Boronline in the event of a dilution. As it can be seen from the graph, in these conditions (dilution rate = -0.16 ppm/s ; threshold = 2420 ppm) the response time would be as low as 5 minutes for a non-intrusive sensor. This means that an alarm will be raised 5 minutes later only after the real fluid crosses the threshold.

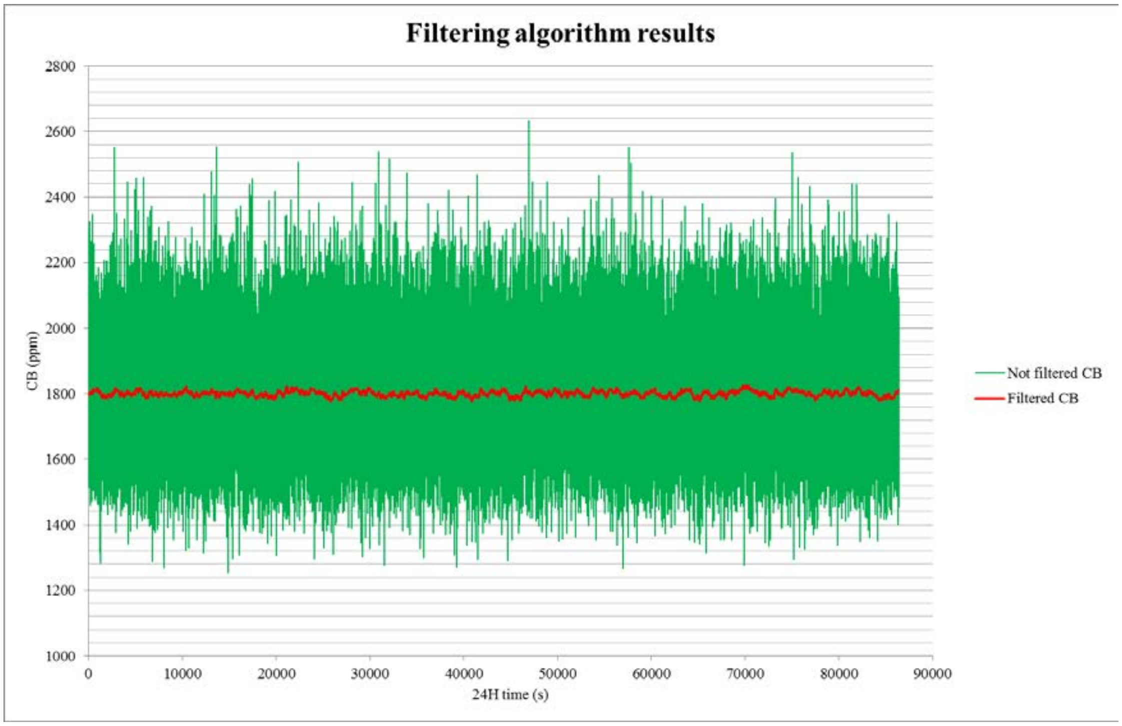

Figure 5: Boron concentration output before and after filtering (24H data recording)

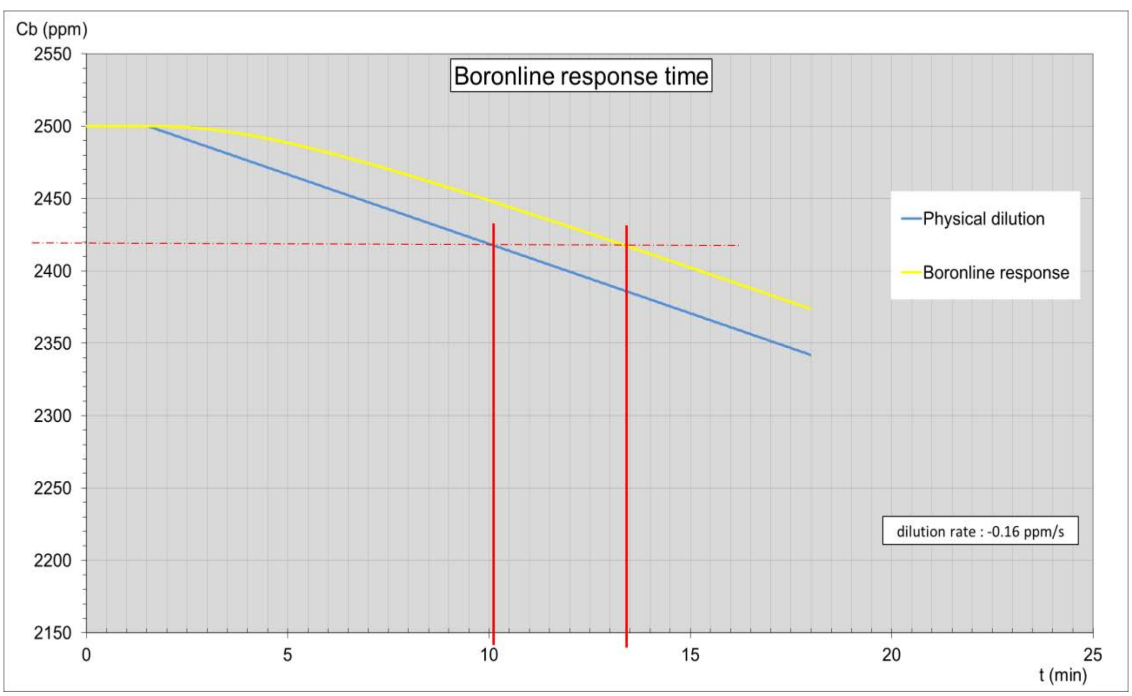

Figure 6: Response Time

5 CONCLUSIONS

The present paper has presented what a boron meter is, its importance regarding safety of nuclear power plants and the characteristics of the newest Rolls-Royce boron meter, Boronline. This paper highlights the importance of providing nuclear power plants with continuous, reliable measurement of boron concentration, and shows how Boronline fulfills this function.

The graphs and the data indicated previously highlight the importance of the filtering algorithm of Boronline. Not only its filter improves accuracy, but it does it with no need to increase signal integration time, thus with no increase of response time. Thanks to that, the compromise between precision and response time is better than ever.