

# VALIDATION OF A METHODOLOGY TO DEVELOP A TEST FACILITY IN REDUCED SCALE RELATED TO BORON DISPERSION IN A PRESSURIZER OF AN iPWR

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## ABSTRACT

The conception and the project of a 1:200 reduced scale test facility have been developed in earlier researches [1,2,3,4]. Such a facility aims to investigate boron homogenization process inside the pressurizer of an iPWR (integral PWR) by considering water mixing from this component with that coming from the reactor core. For this kind of reactor, the pressurizer is located at the top of the pressure vessel demanding the need of identifying the proper mechanisms in order to warrant an adequate homogenization for the water mixture. Once the installation of the experimental setup was concluded, its behavior has been analyzed by considering the concentration of a tracer diluted in the circulation water, whose measurements were obtained at the pressurizer outlet orifices. Two experiments representing boration(boron concentration increase)/deboron(boron concentration decrease) scenarios have been accomplished. Sample acquisition was carried out for every ten minutes during a total time equal to 180 minutes. Results showed that the combination of Fractional Scaling Analysis with local Froude number consisted of an appropriate methodology to provide the reduced scale test facility parameters, inasmuch the measured concentrations from the experiments reproduced the theoretical behavior with sufficient accuracy.

## 1. INTRODUCTION

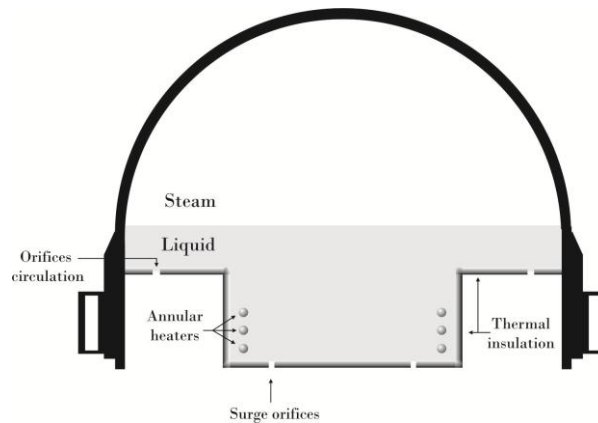
Nuclear industry has been presenting great interest in SMRs (Small Modular Reactors) due to an existence of a high potential market for generating electricity by a clean, safe and economically competitive way. SMRs come out as an option for countries having a small or medium electrical grid, beyond possessing a huge flexibility in its location and process heat applications. Based on four-decade technology for large PWRs, iPWRs (integral Pressurized Water Reactors) represent SMR category with the greatest chances of being available on the market by 2030.

A test facility was built and utilized in order to validate reliable computational models to develop a real scale project and to provide an answer for technical requisites related to boron homogenization of an iPWR pressurizer.

Two experiments analyzing tracer homogenization were carried out in the present research in order to check the adopted methodology to obtain the parameters of a reduced scale facility. Sodium chloride dissolved in water was used as a tracer and the concentration values were taken at the outlet orifices for every 10 minutes during a total time equal to 180 minutes.

## 2. iPWR PRESSURIZER

The pressurizer geometrical configuration of the small modular reactor iPWR is represented in Fig 1.



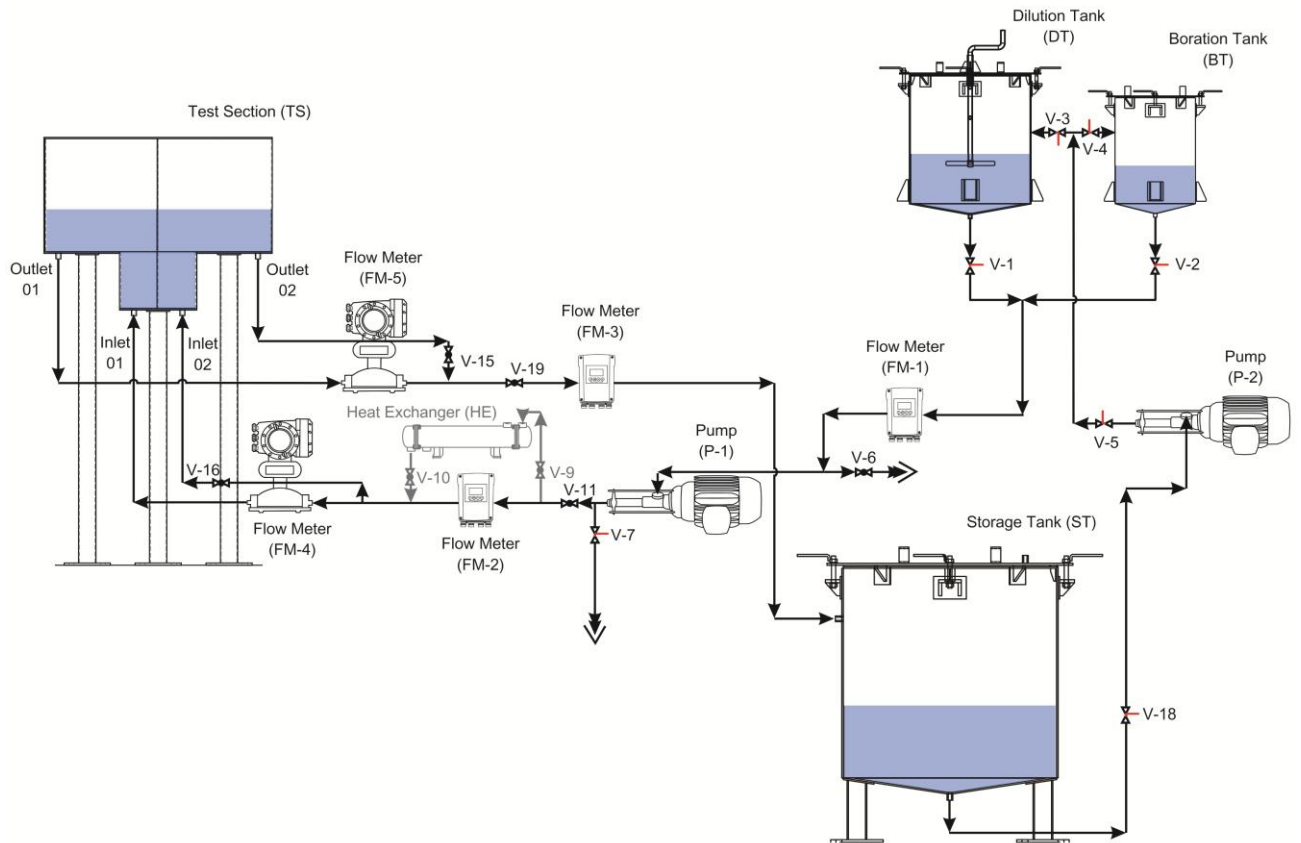
**Figure 1: Lateral view of the iPWR pressurizer (Font: adapted from [5]).**

The saturated water in pressurizer is separated from the reactor primary sub-cooled water by an internal structure with an “inverted hat shape”. The function of this structure includes: (a) preventing the head closure flange and its seals from being exposed to the temperature difference between the reactor and pressurizer water, thus reducing thermal stresses and maintaining sealing tightness; (b) providing an effective thermal insulation to minimize heat transfer to maintain an adequate saturated water layer within the pressurizer; (c) providing structural support for the CRDM drive lines, core instrumentation tubes, and heaters; and (d) providing the communication flow paths between the reactor and pressurizer for the surge flows [5].

## 3. THE TEST FACILITY

The test facility built for experimental investigations of boron dispersion in the pressurizer of the iPWR is located at the Northeast Regional Nuclear Sciences Center (CRCN-NE). The main parameters of test facility were determined through the combination of Fractional Scaling Analysis and local scaling [1]. The construction in reduced scale guarantees the similarity of phenomena with reduction in time and costs.

The general configuration of the test facility is shown schematically in Figure 2. This facility comprehends a boration tank (BT), a dilution tank (DT), a storage tank (TA), a heat exchanger (HE), two pumps (P-1 and P-2), five flow meters and a test section (TS).



**Figure 2. Design of the test facility**

The test section (TS) is made of stainless steel with  $0.092 \text{ m}^3$  capacity, corresponding to one-fourth of the small modular reactor pressurizer in reduced scale of 1:200. It has two inlet orifices and two outlet orifices simulating mass flow inlets and outlets, respectively. The test section is shown the Figure 3. The boron concentration is modeled by the concentration field of a tracer solution.



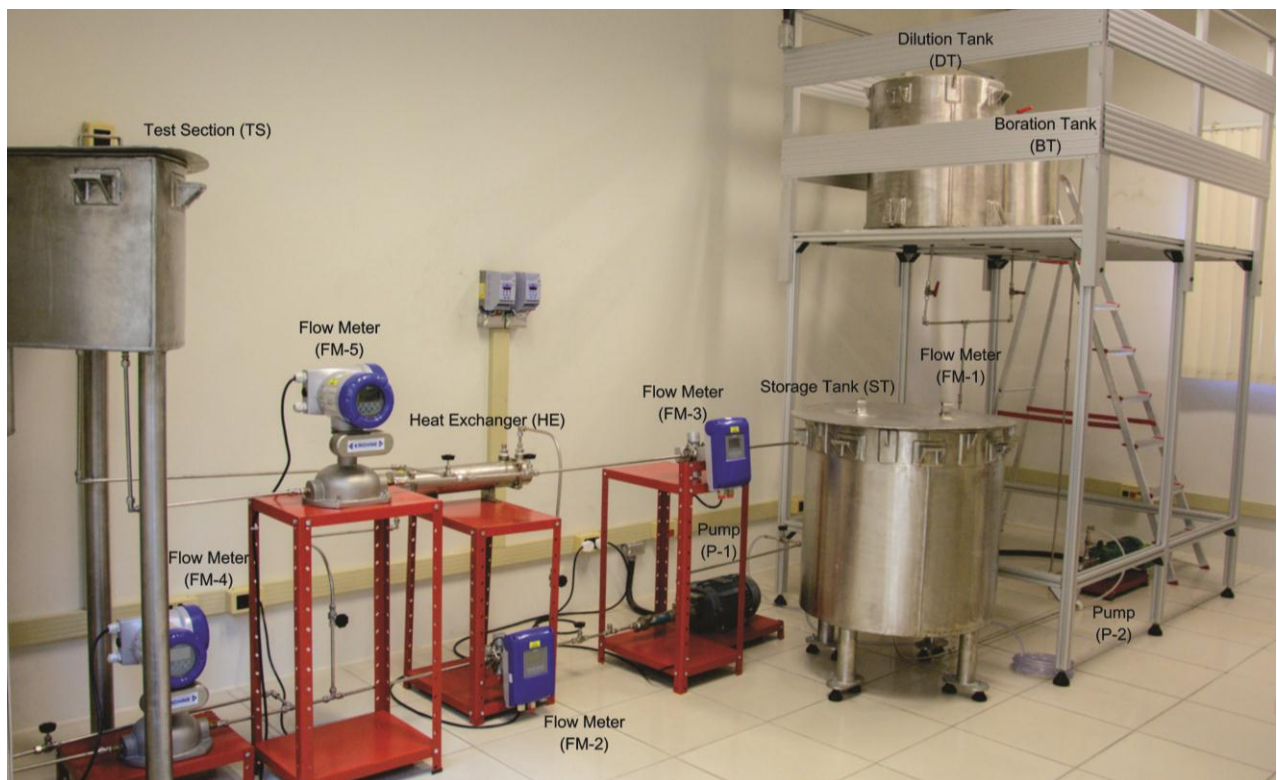
**Figure 3: The test section (TS).**

The tanks (boration, dilution and storage) are made of stainless steel with capacity of  $0.143$ ,  $0.069$  and  $0.216 \text{ m}^3$ , respectively. The two pumps are of positive displacement type NEMO NETZSCH, models BY NM 008 03 S 12 B and NM 011 BY 02 S 12 B. WEG frequency

inverters, CFW-08 0040 B 2024 PSZ and CFW-08 0040 B 2024 PSZ make the control drive and operation of the pumps.

Two types of KROHNE flow meters were installed; three of them were electromagnetic meters, model OPTIFLUX KC1000C/6 (FM-1, FM-2 and FM-3) and two were mass analyzers, model OPTIMASS 3000 H03 (FM-4 and FM-5).

About 95% of the connecting lines are made of stainless steel pipes with nominal diameter of 3/8". For the other remaining 5%, natural polyethylene pipes were installed with the same diameter. All connections used for the experimental set are built by HOKE GYROLOK, made of stainless steel 316, adapted to accommodate the piping. The general arrangement of the items making up the experimental setup is shown in Figure 4.



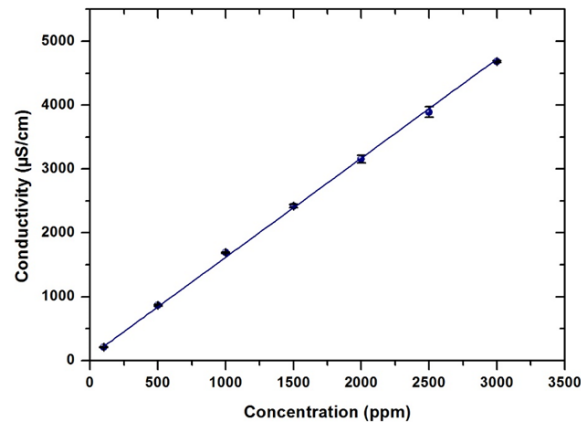
**Figure 4. The test facility**

It is possible to fill the test section (TS) by two different ways: (i) from boration tank (BT), and (ii) from dilution tank (DT). The flow rate will be equally divided among two stainless steel pipes simulating mass flow inlets. The test facility is operated with distilled water.

#### **4. CONCENTRATION MEASUREMENT**

The simulation of boron mixing was accomplished by using sodium chloride (NaCl) as the tracer element. To verify the dependence of the electrical conductivity as a function of NaCl concentration, samples were prepared with a concentration varying from 100 to 3000 ppm. The conductivity measurement was determined with the CELTEC conductivity meter, model FA2104N. The temperature correction is automatic. Before the data acquisition, the

conductivity meter was calibrated using a standard solution. A calibration curve to electrical conductivity (in  $\mu\text{S}/\text{cm}$ ) versus concentration (in ppm) was initially obtained (Figure 5).



**Figure 5: Curve electrical conductivity versus concentration.**

The calibration curve for electrical conductivity versus concentration presents a linear behavior. Table 1 shows the slope, the intercept and the quadratic coefficient of linear correlation ( $R^2$ ) for this curve.

**Table 1: Parameters of electrical conductivity versus concentration**

	slope ( $\mu\text{S}/\text{cm}$ )	Intercept ( $\mu\text{S}/\text{cm}$ )	$R^2$
NaCl	1.552	66.997	0.9993

The combined uncertainty ( $u_c$ ) and the expanded uncertainty ( $U$ ) for the concentration were determined according to Guide to the Expression of Uncertainty in Measurement (GUM) [6]. The calculated values are  $u_c = 9.86\%$  and  $U = 19.9\%$ , with coverage factor equal to 2.017. The value of the coverage factor was determined by using the Student's distribution with confidence level of 95.45 %.

## 5. BOUNDARY CONDITIONS OF THE EXPERIMENT

Two experiments were conducted to evaluate the potential of the test facility to determine the concentration of the injected tracer element at the inlet/outlet of the test section. The experiments were executed without heating. Thus the valves V-9 and V-10 remained closed, and the heat exchanger (TC) was not used. Initially all pipes were carefully filled with distilled water.

### 5.1. Experiment 1

In the experiment 1, the test section had only distilled water and was filled continuously with a solution with a known concentration of NaCl. For this experiment, the test section, the boration tank and dilution tank were filled with distilled water to a volume equivalent to

0.0405, 0.060 to 0.100 m<sup>3</sup> respectively. By keeping the test section with a volume of 0.0405 m<sup>3</sup> ensures the necessary similarity found in [1]. The filling of these tanks and pipes assembly has been carefully carried out, ensuring that the pipes does not contain air. The storage tank was used as a reservoir for conditioning water coming from the test section.

A constant flow of input and output test section with the borating water tank was established. Distilled water from dilution tank was used to prepare a solution with concentration of 1000 ppm. After preparation of the solution, V-2 valve was closed and the V-1 valve was opened, interrupting the supply of distilled water in the circuit and inserting a solution with a concentration of 1000 ppm which fed TS throughout the experiment 1.

The average flow rate was  $2.89 \times 10^{-6}$  m<sup>3</sup>/s. A sample with 100 ml was extracted every ten minutes, during a period of 180 min, to quantify the concentration. These samples were analyzed by an electrical conductivity meter (using microprocessor conductivity meter of CELTAC, properly calibrated) estimating thus the tracer element concentration.

## 5.2. Experiment 2

In experiment 2 the test section (TS) was analyzed with an equivalent volume equal to 0.0405 m<sup>3</sup> by using a solution having a NaCl concentration of 1000 ppm. After establishing an equivalence between the volumetric flow in and out of the test section, a steady flow of distilled water in ST was injected. Thus, the concentration of the test section gradually decreased.

When the volumetric flow rate was stabilized at  $2.33 \times 10^{-6}$  m<sup>3</sup>/s, V-1 valve was closed and, concurrently, the valve V-2 was opened. Thus, the test section was fed with only distilled water. To quantify the concentration at the inlet and outlet sections, 100 ml samples were taken every 10 minutes interval for 180 minutes. The electrical conductivity of these samples was determined using the microprocessor conductivity meter CELTAC and from the calibration curve, NaCl concentrations were estimated.

## 6. PARAMETERS USED IN THE EXPERIMENTS

The characteristics that defined the execution of experiments, and the core values that have characterized the results are presented in the Table 2.

**Table 2: Parameters used in the experiments.**

	<b>Exp.1</b>	<b>Exp.2</b>
<b>Scenario</b>	Boration	Deboration
<b>Initial Concentration in TS (ppm)</b>	0	1000
<b>Concentration in the external tank (ppm)</b>	1000	0
<b>TS Volume (m<sup>3</sup>)</b>	0.0405	0.0405
<b>Volumetric flow rate (m<sup>3</sup>/s)</b>	$2.89 \times 10^{-6}$	$2.33 \times 10^{-6}$
<b>Duration of the experiment (s)</b>	10800	10800

## 7. EXPERIMENTAL RESULTS

### 7.1. Experiment 1

The representation of a borating scenario conducted in the experimental setup allowed the identification of the behavior of salt concentration at the inlet and outlet of the test section for a period of 180 minutes. Each experimental point is the average of three successive readings.

The first order exponential function that fits the experimental data is shown in Equation 1, where  $C$  is the concentration in ppm and  $t$  the time in minutes. The correlation factor,  $R^2$ , found for this fitting is 0.994.

$$C = 998,14 - 976,80 \cdot e^{-\left(\frac{1}{284,67}\right)t} \quad (1)$$

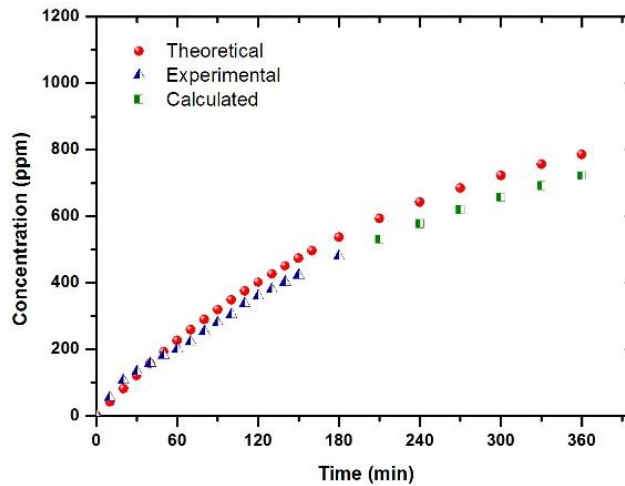
According to the literature (1), concentration,  $C'$  as a function of time,  $t$ , can be determined from Equation (2).

$$C' = C_E + (C_0 - C_E) \cdot e^{-\alpha t} \quad (2)$$

In that  $C_E$  is an initial concentration (constant value) injected from an external reservoir which is responsible for varying the primary concentration;  $C_0$  is the initial concentration of boron in the water of the primary circuit and the factor  $\alpha$  is the ratio of the injected mass flow  $w'$ , and the primary mass  $M'$ .

$$\alpha = \frac{w'}{M'} \quad (3)$$

With these parameters it was possible to determine the theoretical concentration over 6 hours in order to compare the results with the theoretical values obtained through the experiment 1. As the experiment was conducted over 3 hours only, Equation (1) was used to extrapolate the concentration amounts between 3 and 6 hours. The concentration values determined from Equation (2), called theoretical values, the experimental values at the output, and the values calculated by Equation (1) as a function of time are shown in Figure 6.



**Figure 6: Concentration versus time during the experiment 1, found from the theoretical, experimental and the curve fit.**

Comparing the theoretical values with the experimental values, the percent deviation between them was close to 10%.

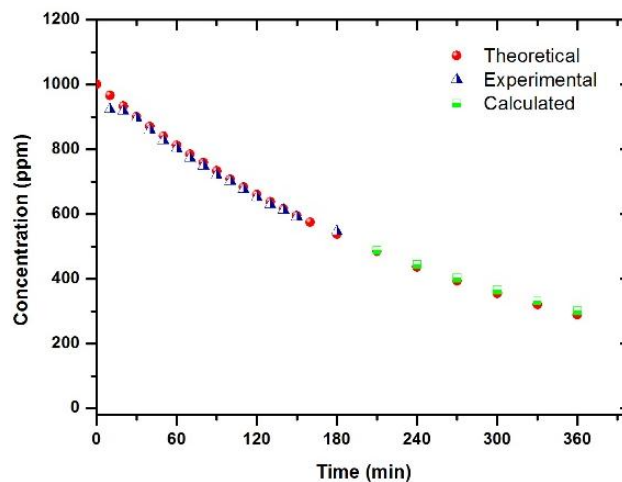
## 7.2. Experiment 2

For the representation of a deboration scenario, the same general procedure was adopted as in Experiment 1.

Now, the function that fits the experimental data is shown in Equation (4), where C is the concentration in ppm and t the time in minutes. The correlation factor,  $R^2$ , found for this fitting was equal to 0.996.

$$C = 11,71 + 962,43 \cdot e^{-\left(\frac{1}{299,00}\right)t} \quad (4)$$

The theoretical values of concentration, concentration values determined experimentally at the output of the test section and extrapolated concentrations calculated after 180 min with Equation (4) as a function of time are shown in Figure 7.



**Figure 7: Concentration versus time during the experiment 2, found from the theoretical, experimental and the curve fit.**

By comparing the experimental results with theoretical results, it was verified that deviations are less than 5%.

## 8. CONCLUSION

The project for the test facility aimed to provide relevant data for boron homogenization phenomena in the pressurizer of an integral, compact modular reactor. Two experiments were conducted at the experimental setup, all at room temperature and using only an input and an output of the test section. After the execution of the experimental setup and the experiments, it was possible to prove the feasibility of using the experimental installation, reliably, for values that constitute boration and deboration scenarios in a pressurizer of an iPWR reactor.



The consolidation of the design of an experimental set scaled to the study of boron homogenizing processes in a pressurizer of an iPWR is a contribution that will provide to the academic community an additional facility to acquire knowledge of the phenomena involved.

## ACKNOWLEDGMENTS

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