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Technical note

Study of the boron homogenizing process employing an experimental low-pressure bench simulating the IRIS reactor pressurizer – Part II

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ABSTRACT

The reactivity control of a nuclear reactor to pressurized water is made by means of controlling bars or by boron dilution in the water from the coolant of a primary circuit. The control with boron dilution has great importance, despite inserting small variations in the reactivity in the reactor, as it does not significantly affect the distribution of the neutron flux.

A simplified experimental bench with a test section manufactured in transparent acrylic, was built in reduced scale as to be used in a boron homogenizing process, simulating an IRIS reactor pressurizer (International Reactor Innovative and Secure). The bench was assembled in the Centro Regional de Ciências Nucleares do Nordeste (CRCN-NE), an entity linked to the Comissão Nacional de Energia Nuclear (CNEN), Recife–PE.

1. Introduction

On Part I of this paper, we saw that the pressurizer is an important component in the functioning of a PWR since it controls SRR pressure keeping it under-cooled, performing this control through electric heaters and valves for squirting water. During normal reactor operation, system pressure is controlled by the pressurizer through the aspersion valves and electric heaters, which keep the pressurizer temperature at a reference value.

IRIS is a generation III+ modular reactor, refrigerated by pressurized light water, with an integral configuration (Carelli, 2003).

Boron (B^{10}) is an excellent absorber of thermal neutrons and, in the form of boric acid diluted in the coolant of the PWR, it is used for controlling reactivity. From Beginning of Life (BOL) to End of Life (EOL) of a reactor fuel cycle, the boron concentration in SRR is reduced for compensating the fuel burn. The question of homogenization becomes an important safety factor in operating a reactor, in function of inadequate procedures for boron homogenization.

2. Theory

The accident analysis is crucial in the safety area of the nuclear centrals. From the hypothesis of accidents formulation, the behavior of the central is studied and the criteria, which determine the condition for a safe operation, are established. The plants are licensed for operation with the guarantee that accidents and postulated transients do not surpass the safety limits established by technical specifications.

2.1. Pressurized water reactors (PWRs)

The PWR reactor, the most widely used power reactor in the world, uses light water as cooler, moderator and reflector. The main characteristic of a PWR unit is the pressured cooling water (primary circuit), always keeping a liquid phase once the pressure varies from 14 to 17 MPa. The reactor refrigerator removes the heat generated by the core and, also, works as a moderator, reducing the neutrons energy which will produce the fissions in the fuel elements and generate heat. Besides, it also functions as a neutrons reflector, reducing their escape from the interior of the vase of the reactor and also serving as a solvent means of the boric acid which is used to aid in the control of the generation of the power in the nucleus, once it absorbs neutrons and with this, it can be used as to control the fissions reactions, In the interior of the reactor vase, the combustible elements heat the refrigerator, which

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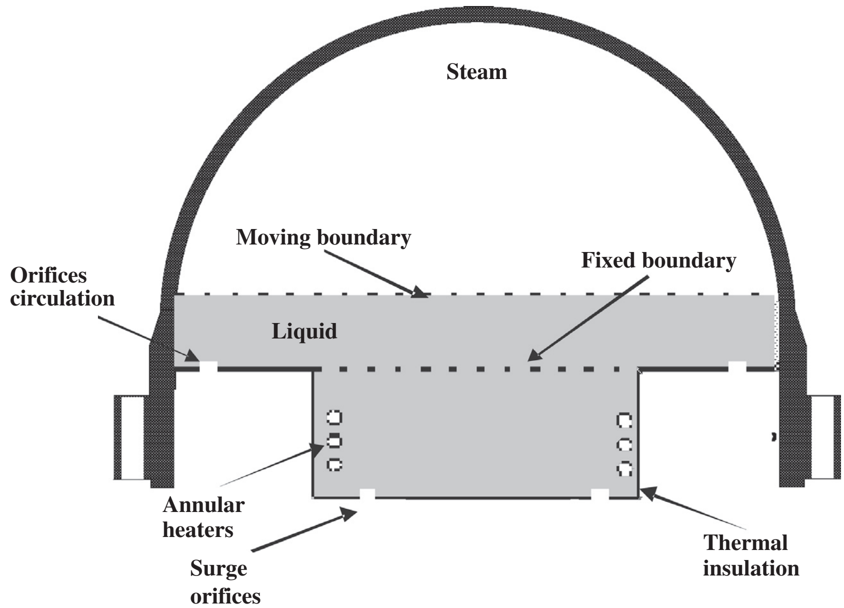

Fig. 1. Transversal cut of the IRIS pressurizer.

Fig. 2. Experimental set.

remains sub-refrigerated (temperature below the saturation point, for the existing pressure), in the sequence, it is taken to the steam generators where it will transfer heat, through tubes for the feeding water which is in the interior of the GVs.

2.2. Pressurizer of PWR

In the pressurizer of a PWR, saturated liquid and vapor coexist in balance and, thus, maintain the RCS under-cooled, since the temperature of the PZR is greater than that of the RCS. The maintenance of the balance between saturated liquid and vapor makes it possible to control RCS pressure. The pressurizer is a vertical, cylindrical container, with the superior and inferior hemispheric lids made in carbon steel, coated with austenitic stainless steel on all surfaces in contact with the reactor coolant. Immersion electric heaters are set up on the base of the container while the junctions of the spray line, relief valves and safety valves are set up on the superior lid of the container.

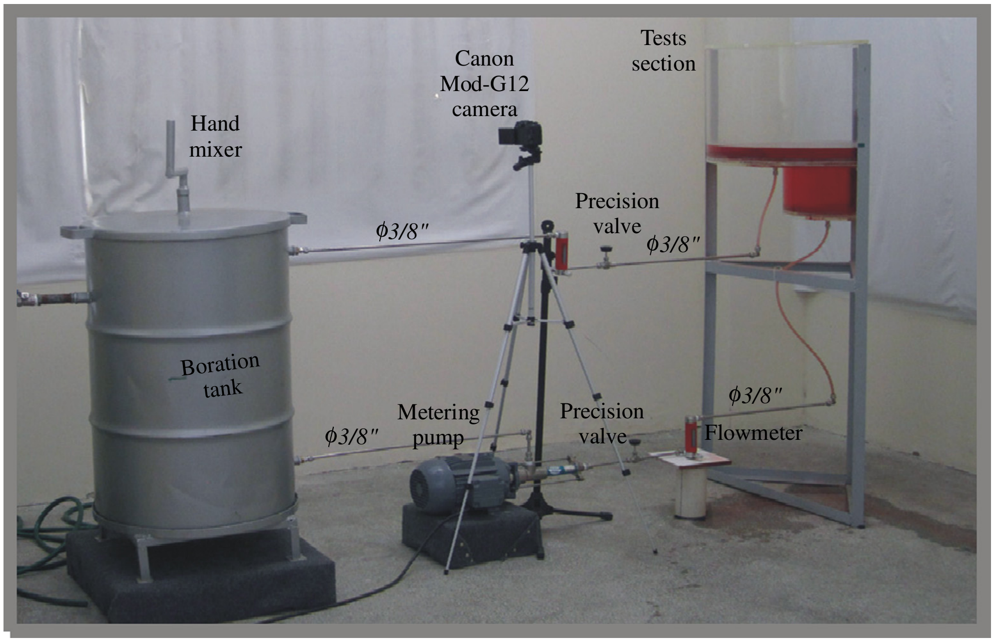

Fig. 3. Device used for acquiring the pictures and videos during the experiments.

Table 1
Data referring to the experiments.

Power (%)	Contration (ppm)	Tests section (%)	Boration tank (%)	Orifice diameter (mm)	Dye (color)
Experiment – A					
100	100	40.5	100	10	Blue
Experiment – B					
20	400	40.4	100	10	Blue
Experiment – C					
0	1000	17.0	100	10	Blue

Table 2
Experiment A data.

Time (h)	Gray shades	Gray Shades/N	Note
Beginning	91.15	0.490	$t = 0.03$ h
0.5	144.20	0.776	
1.0	149.85	0.807	$N = 185.80$
1.5	167.85	0.903	
2.0	182.20	0.981	
2.5	168.30	0.906	
3.0	178.40	0.960	
3.5	178.80	0.962	
4.0	184.25	0.992	
4.5	185.80	1.000	

Table 3
Experiment B data.

Time (h)	Gray shades	Gray shades/N	Note
0.083	130.5	0.636	
0.166	148.8	0.725	
0.250	162.7	0.793	$N = 185.8$
0.333	181.1	0.881	
0.500	174.1	0.849	
1.000	190.1	0.927	
1.500	201.9	0.984	
2.500	205.0	0.999	
3.000	203.2	0.976	
3.500	205.2	1.000	

Table 4
Experiment C data.

Time (h)	Gray shades	Gray shades/N	Note
0.083	143.5	0.634	
0.166	174.9	0.770	
0.250	182.2	0.802	$N = 227.2$
0.333	192.7	0.848	
0.500	222.7	0.980	
1.000	219.9	0.968	
1.500	227.2	1.000	
2.000	225.9	0.994	
2.500	224.8	0.989	
3.000	226.4	0.996	

The pressurizer is designed to accommodate the volumetric expansions and contractions caused by load variation. The surge line, which leaves from the base of the pressurizer, connects the pressurizer to the hot leg of the primary circuit of the RCS. During volumetric expansions (due to temperature increase) the spray system, whose water comes from the cold legs of the RCS, condenses part of the vapor existing in the pressurizer, preventing the pressure from reaching the value which triggers the release valves.

During volumetric contractions of the RCS, the transformation from water into vapor and consequent generation of vapor by automatic action of the heaters keep pressure above the value at which the reactor shuts down due to low pressure. The heaters are also energized when a high level of water comes to the pressurizer from the RCS.

2.3. IRIS reactor

The project of an integral reactor contributes to the elimination of accidents, which does not occur in PWR, for instance. IRIS (International Reactor Innovative and Secure) is a generation III+ modular reactor, cooled with pressurized light water, with an

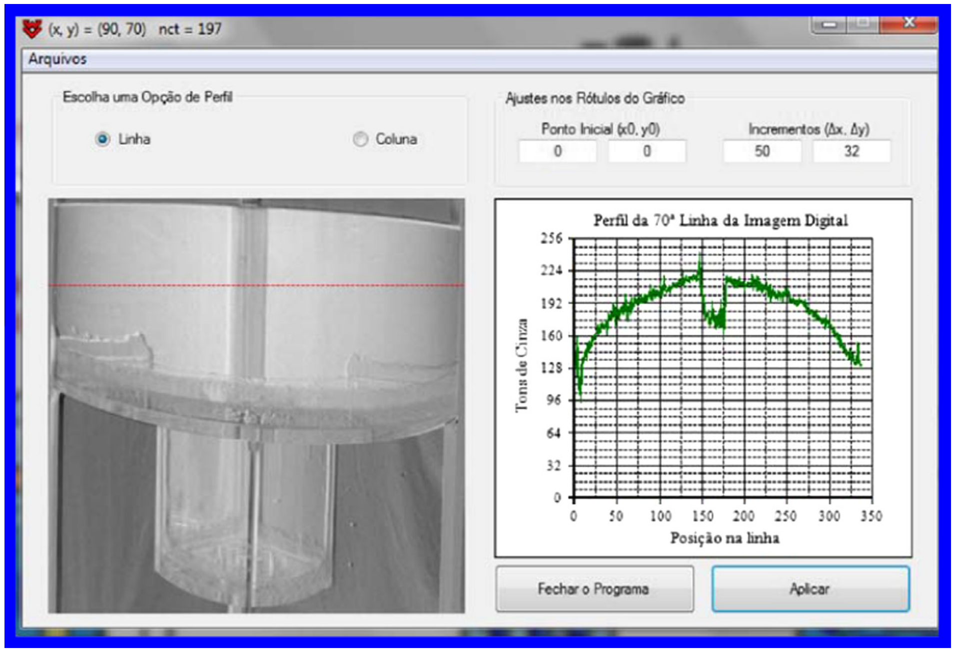

Fig. 4. Processed image of the upper region of the ST – ($t = 2$ h).

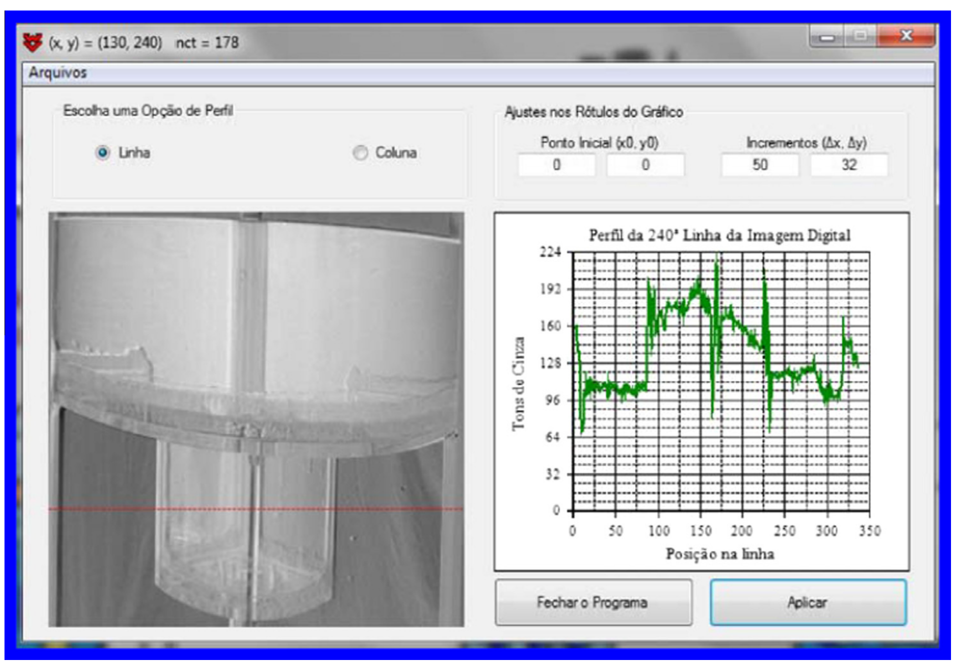

Fig. 5. Processed image of the lower region of the ST – ($t = 2$ h).

integral configuration. The IRIS reactor project is the outcome of a consortium involving 20 organizations and nine countries, managed by Westinghouse. The occurrence of the loss of coolant accidents (LOCA) is practically eliminated, given that in this type of reactor there are no long tubing systems (Carelli et al., 2004; Filho, 2011).

2.4. IRIS pressurizer

The pressurizer of the IRIS reactor is located in the upper part of the reactor's container for pressure. Water from the pressurizer is separated from the water of the cooling fluid of the primary circuit by an internal structure with the shape of an inverted hat, as show in Fig. 1 (Barroso et al., 2003; Botelho et al., 2005). This structures attenuates the heat transfer, keeping the water saturated in the interior of the pressurizer. The heaters are located in the lower part of the pressurizer; the surge orifices, through which the water of the primary system flows, are also located in this region.

When a PWR is shut down, the boron in the coolant has the function of keeping the reactor in a state of sub-criticality. If the water with low boron concentration is introduced accidentally, it is necessary to perform a homogenization so that the water volumes with a small quantity of boron do not reach the reactor container and restart a chain reaction.

2.5. Problems in the boron homogenization

Studies of transients with boron homogenizing deficiency in PWRs have been very highlighted in the last years. One solution of boric acid is normally added to the coolant of the primary circuit, aiding the fission rate control in the reactorś nucleus. Such system, normally is not able to control alone the reactivity as the change in the boron concentration does not act so rapidly as to satisfy the safety requisites, as the control bars do (Silva, 2008). When a PWR reactor is turned off, the remaining boron in the coolant has the function of maintaining the reactor in a state of sub criticality. If water with low boron concentration is introduced accidentally, it is necessary to make a homogenization, so that the water volumes with low boron quantities do not reach the reactor vase and restart a chain reaction.

3. Methodology

In Fig. 2, there is a photography of the experimental set used for studying the boron homogenization process in the IRIS nuclear reactor. Its assembly was based on the study developed by Silva et al. (2010, 2011), who determined in their work the parameters of a section of tests for the pressurizer of the IRIS reactor, utilizing a methodology of similarity known as Fractional Scale Analysis (Zuber et al., 2005; Wulff et al., 2005). The simplified set has two tanks with volumes of 200 liters each, where the dilution and boration processes take place, a dosing pump, frequency counter, two flowmeters for measuring flow rate, precision valves in stainless steel, brass ball valves, connections and tubes with inner diameter of 3/8″ in stainless steel. The test section, representing 1/4 of the IRIS pressurizer, was built with transparent acrylic, 20 mm thick at the largest and smallest bases of the cylinders, and the side walls in transparent acrylic with 10 mm thickness.

Fig. 3 shows the device used for acquiring the pictures and videos during the execution of the experiments.

3.1. Experiments

The data referring to the experiments carried out in this paper are shown in Table 1.

3.2. Theoretical model

The theoretical model (Narain, 2012) which describes the experiments simulated in the experimental set is described by the equations:

$$V_1 \frac{dC_1}{dt} = Q[C_2 - C_1] \tag{1}$$

$$V_2 \frac{dC_2}{dt} = Q[C_1 - C_2] \tag{2}$$

where C1 is the concentration in the tests section, C2 is the concentration in the boration tank, V1 is the volume in the tests section, V2 is the volume in the boration tank and Q is the flow rate at the entry and exit in the tests section.

The solution of the system formed by Eqs (1) and (2) is:

$$C_1(t) = C_2(0)\left(\frac{T_2}{T_1+T_2}\right)\left[1 - e^{-\left(\frac{1}{T_1}+\frac{1}{T_2}\right)t}\right] \tag{3}$$

$$C_2(t) = C_2(0)\left[\frac{T_2}{T_1+T_2} + \frac{T_1}{T_1+T_2}e^{-\left(\frac{1}{T_1}+\frac{1}{T_2}\right)t}\right] \tag{4}$$

where

$$T_1 = \frac{V_1}{Q} \quad \text{and} \quad T_2 = \frac{V_2}{Q}$$

4. Results

The experimental results were obtained through videos and digital pictures at the tests section (Canon Mod-G12 camera), during the homogenization process. In the execution of the experiments, a dye with properties similar to boric acid was used to allow for visualization. The evolution of the dye plume in the ST was registered at every 30 min, during a time of approximately 5 h, when there was a visual indication of the homogenization of the dye in the system. The pictures obtained were processed with the DIP (Digital Image Processing) program (Vieira and Lima, 2009). The results obtained with DIP made it possible to quantify the value of the concentration of dye through time in the tests section (Bezerra et al., 2013).

Tables 2–4 show the summaries of the measurements carried out in experiments A, B and C. The gray tones shown in the tables are mean values, obtained in the superior and inferior region of the ST, as shown in Figs. 4 and Fig. 5 of experiment A, for a measurement with a two hours time period. Figs. 6–8 show, respectively, graphics of normalized concentrations in function of time, for experiments A, B and C, obtained experimentally and with the theoretical model. It is possible to observe in the three curves that the homogenization time of the dye in the system occurs in about

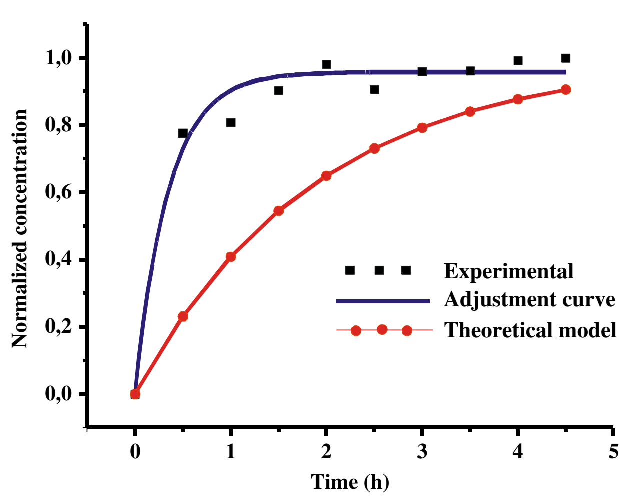

Fig. 6. Normalized concentration x time – Experiment A.

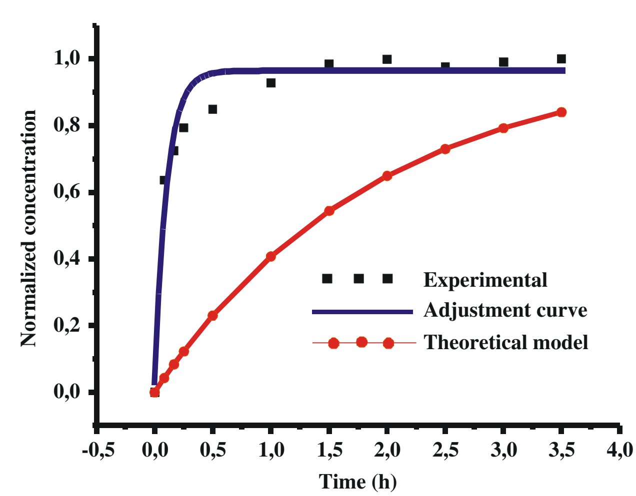

Fig. 7. Normalized concentration x time – Experiment B.

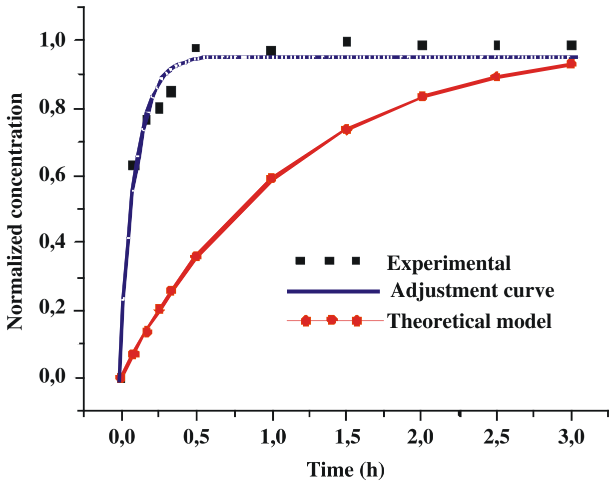

Fig. 8. Normalized concentration x time – Experiment C.

three hours, that is, from that moment on the asymptotic behavior of curves begins.

5. Conclusions

The results obtained experimentally have shown, from a qualitative and quantitative point of view, a good concordance with the results of the theoretical model, given that both curves (experimental and theoretical) presented the same asymptotic behavior. Mean homogenization time of the dye in the system was of about three hours for all three experiments. The curve of the theoretical model shows also that in this time the homogenization of the system tends to stabilize.

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