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AN EXPERIMENTAL LOW-PRESSURE FACILITY TO STUDY BORON TRANSIENTS IN THE PRESSURIZER OF AN INTEGRAL MODULAR NUCLEAR REACTOR

Samira R. V. Nascimento[1], Carlos A. B. O. Lira[1], Celso M. F. Lapa[2], Jair L. Bezerra[3], Mário A. B. Silva[1], Fernando R. A. Lima[3], Antônio C. O. Barroso[4], Maria de Lourdes Moreira[2]

[1] Departamento de Energia Nuclear – DEN/UFPE
Universidade Federal de Pernambuco
Av. Professor Luiz Freire, 1000
50740-540 Recife, PE
samiraruana@gmail.com

[2] Instituto de Engenharia Nuclear – IEN/CNEN-RJ
Programa de Pós-Graduação em Ciência e Tecnologia Nucleares
Rua Hélio de Almeida, 75
21941-972 Rio de Janeiro, RJ
lapa@ien.gov.br

[3] Centro Regional de Ciências Nucleares – CRCN/CNEN-NE
Comissão Nacional de Energia Nuclear
Av. Professor Luiz Freire, 200
50740-540 Recife, PE
falima@crcn.gov.br

[4] Instituto de Pesquisas Energéticas e Nucleares – IPEN/CNEN-SP
Comissão Nacional de Energia Nuclear
Av. Professor Lineu Prestes, 2242
05508-000 São Paulo, SP
barroso@ipen.br

ABSTRACT

Small and medium size modular reactors offer many advantages when compared with typical nuclear plants in various circumstances, such as offering greater simplicity of design, economy of mass production, and reducing siting costs. The integral configuration is characterized by having most of its components inside the pressure vessel, eliminating the probability of accidents. However, for this configuration there is no spray system for boron homogenization, which may cause power transients. Thus, it is necessary to investigate boron mixing. The Federal University of Pernambuco (UFPE), in a partnership with the Regional Center of Nuclear Sciences of Northeast (CRCN-NE) and the Nuclear Engineering Institute (IEN/CNEN-RJ), is developing a project that aims to analyze transients in a compact modular integral reactor. This analysis will be made by using the data obtained from one experimental bench that is mounted at CRCN-NE. A study accomplished in 2012 using a simplified bench (built in reduced scale with a test section manufactured with transparent acrylic) showed that it was possible to obtain preliminary experimental results for the boron homogenizing process.

1. INTRODUCTION

Designs for small modular reactors (SMRs) have been developed in several countries, like Argentina, China, Japan, Korea, Russia, South Africa and the United States, frequently through cooperation between government and industry [1]. According to the classification adopted by the International Atomic Energy Agency (IAEA), small reactors are those with an equivalent electric power of less than 300 MW(e) and medium size reactors are those with an equivalent electric power between 300 and 700 MW(e). The SMRs are projected with modular technology, reducing expenditures on series production and allowing the fabrication in a short period of time. SMRs designs include a range of technologies, some of them are variants of the Generation IV systems [1]. The development and deployment of SMRs will permit several applications as electricity generation and other non-electrical applications, like seawater desalination, district heating and hydrogen production [2, 3].

Some of the advanced SMRs, as NuScale, mPower and W-SMR, have an integral pressurized water reactor (iPWR) configuration. These SMRs share a common set of design principles like the components of primary system incorporated in only one single vessel, providing the increase of the primary reactor vessel, more effective heat removal, the increase of the pressurizer volume, and the components layout in the vessel, that facilitate the core cooling by natural convection. These features, also adopted by IRIS reactor, use the passive safety systems, guaranteeing the optimization of the installations' safety and its better operation and on the global economy aspects [4].

About the iPWR, the pressurizer is located within the reactor vessel top. This configuration involves changes on the techniques such as the fabrication of a bigger system, without any additional costs [5]. In a pressurizer of a non-integrated nuclear reactor, a spray offers a continuous mini-flow, whose function is to homogenize boron concentration between pressurizer and reactor coolant [6]. On the other hand, the extra capacity of the pressurizer of the iPWR, allows pressure variations with no spray.

It is known that scaled experiments are a useful and practical resource to get more affordable proof of performance. They help to uncover any remaining small flaws of the design and provide ways to optimize design parameters. The similarity of prototypes and their respective scaled models is a key issue in their wide use for the phenomena and processes of interest. Furthermore, real size test facilities are often extremely expensive and usually unpractical [6].

Thus, the aim is to plan and to build an experimental setup with a test section to study the mixing and homogenization of boron in the pressurizer liquid volume as a function of movement mechanisms, which is being considered in the development of an integral modular nuclear reactor. This experimental facility should allow variation of the various parameters of design and operation so that they can optimize the mechanisms of homogenization. Furthermore, it allows the execution of experiments that simulate, on an adequate scale, all the evolutions of the boron concentration.

2. PRESSURIZER

2.1. Conventional pressurizer

The pressurizer shown in Fig. 1 is an important component to control the pressure in the primary coolant system. It provides a surge volume for system coolant expansion and contraction, such that the system pressure can be controlled above saturation [7]. In conventional PWRs, the continuous operation of the sprinkler system (spray) at its minimum flow condition (mini flow), minimizes thermal shock and provides a continuous mix between primary coolant and water in pressurizer, allowing a good mixing between them. This avoids the occurrence of reactivity transients in sequence causing flow surge in the pressurizer.

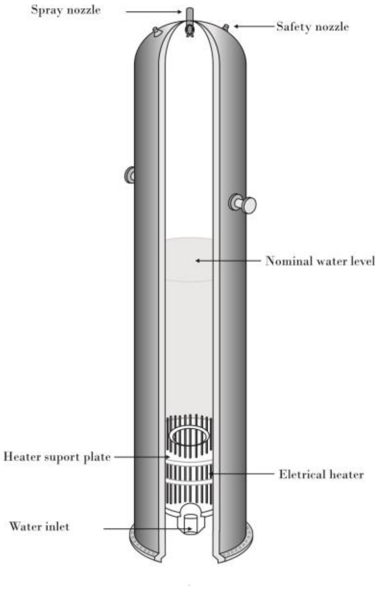


Figure 1: A PWR pressurizer.

2.1. iPWR pressurizer

The iPWR pressurizer is located in the pressure vessel upper head, above the internal control rod mechanisms. In the case of the IRIS pressurizer, in Fig. 2, the absence of the sprinkler requires to investigate the mixture of the boron concentration in the pressurizer and possible differences of the concentration in the primary water. This study is necessary, mainly, in operations of the power increase and reduction in reactor. From economic point of view, the concentration of boron in the primary coolant is adjusted for each power level. The most part of control rods stay outside the core being only that portion of the control banks that is needed to control the reactor power. This way of operation allows for a more homogeneous and better utilization of the fuel.

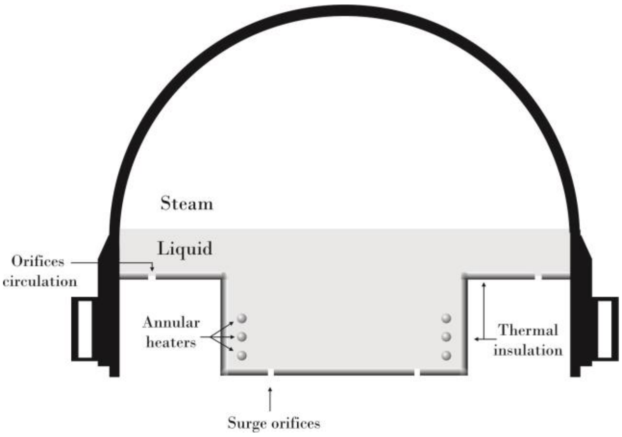


Figure 2: Transversal cut of the IRIS pressurizer.

For each power level the fuel average temperature varies, i.e. the greater the power the greater must be the temperature difference between coolant and fuel for transferring such power. This temperature elevation, than, introduces a negative reactivity, which for practical purposes is measured and mapped for each core configuration using reactivity curves (pcm) vs. % power.

By passing from the condition of Hot Zero Power to hot full power the concentration of boron in the primary coolant has to be reduced. Similarly to reduce the power to shut off, it will have to be increased. On the other hand, the maneuver QPZ - QPP, e.g. implies large influx of water into the pressurizer at the same time that a dilution of boron concentration is being processed in the primary. The maneuver power lasts one to two hours and is operated with the movement of the control rods. Thus during this period the average temperature of the primary varies resulting in the influx of water into the pressurizer. On the other hand, the variation of boron concentration is performed in a longer period, typically from 20 to 30h to compensate other radioactive effects such as increasing of the concentration of xenon and samarium. This means that, during this period, the concentration of boron in the pressurizer deviates from that found in the remainder of primary refrigerant. This discrepancy will be greater the lower the rate of movement between the pressurizer and the full top of the reactor. On the other hand, this rate must be kept as low as possible to reduce thermal loss and not to disturb the layer of saturated liquid that must be maintained in the pressurizer so that it will respond properly to their ability to alleviate the pressure drop in transient cooling of the primary.

3. LOW-PRESSURE FACILITY OVERVIEW

3.1. Low-pressure bench description

A 1:200 scale was adopted to build the model. For cost reduction and due to symmetry, it was decided to represent only ¼ of the pressurizer. The basic dimensions of the volume occupied of Test Section Pressurizer is show in Table 1.

Table 1: Basic Dimensions of Test Section Pressurizer

	Pressurizer IRIS	TS (1/4 of pressurizer and scale 1/200)	
	(m^3)	(m^3)	(l)
Total volume	77.150	0.096	96.438
Liquid volume	32.400	0,041	40.500
Steam volume	44.750	0,056	55.938

The low-pressure facility will have an homogenizing vessel (VH), a boration tank (TB), a dilution tank (TD), a storage tank (TA), a heat exchanger and a test section (TS), as shown in Fig. 3. In the Fig. 4 it is possible to visualize the layout of the tanks.

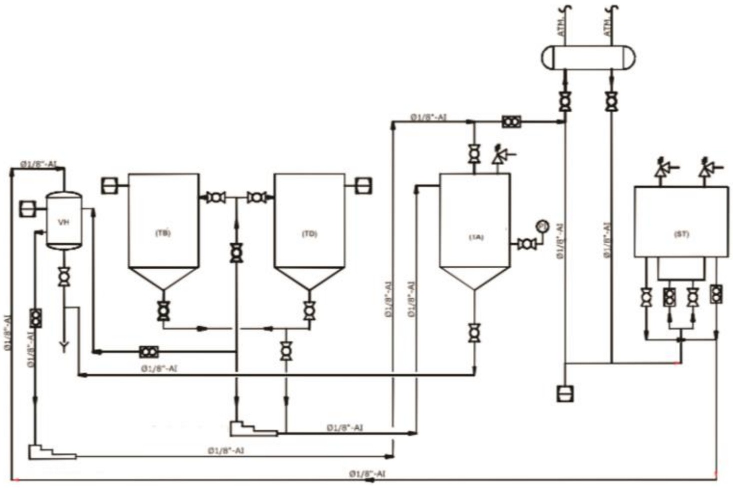


Figure 3: The low-pressure facility flow diagram [8].

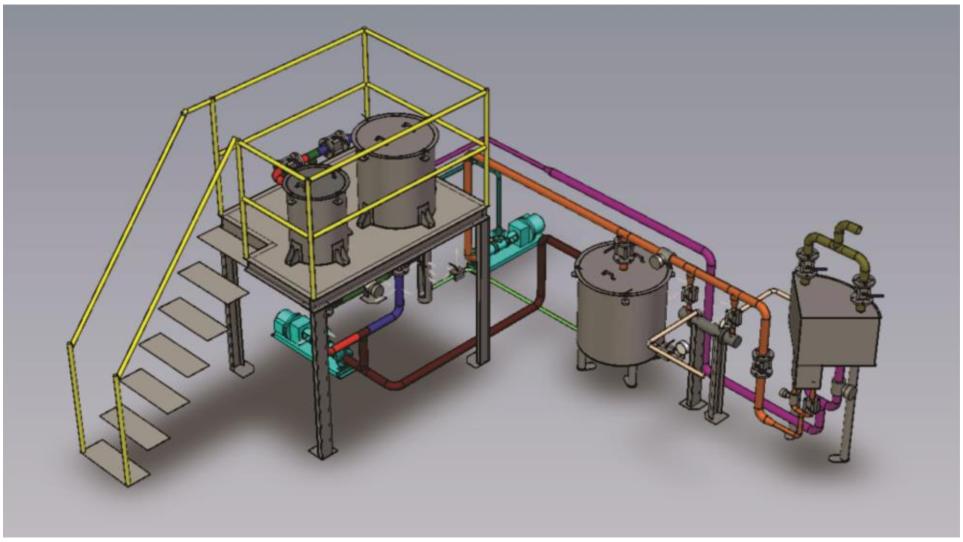


Figure 4: The low-pressure facility flow diagram.

3.2. Test section parameters

A study of similarity has been the subject of a doctoral thesis from which the parameters were obtained to make the design of the bench [8]. Through the combination of Fractional Scaling Analysis and local scaling, it was possible to determine the main parameters of a test section for boron dispersion analysis. This reduced scale system provides many data, which will help in the construction of IRIS pressurizer and of pressurizers with the similar design [6, 9].

By comparing the values for both prototype and model shown in Table 2, it can be seen that the dimensionless equations relative to concentration and time represent both systems with excellent accuracy [9]. The validation of this methodology was also verified when the parameters of the model (obtained by FSA) were inserted in the analytical solution of equation system [8].

Table 2: Dimensionless fractional rates of change [9]

Dimensionless rate	Prototype	Model
$\widehat{w}_1$	25.4676	25.4712
$\widehat{w}_2$	0.7619	0.7621
$\widehat{w}_3$	7.9585	7.9598
$\widehat{w}_4$	0.2381	0.2381

According to estimates done in [8], a thermal power equal to 5500W is enough to maintain similarity between IRIS pressurizer and the test section described in this paper. The main parameters for these systems are shown in Table 3.

Table 3: Main parameters of IRIS and test section [8]

Parameter	Prototype	Model
Liquid water mass (kg)	18,833	151.83
Internal water temperature (K)	620	306.3
Inlet water temperature (K)	603	373
System pressure (MPa)	15.5	0.1
Recirculation flow (m^3/s)	0.000504	0.00001367
Condensation rate (kg/s)	0.00989	0.0004069
Thermal power (kW)	53.91	5.47
Time of transient (s)	108,000	21,168
Surge orifice diameter (m)	0.05	0.0145

3.3. Preliminary studies

The preliminary experimental results were obtained through a simplified experimental bench used in the study of the boron homogenization process in the IRIS nuclear reactor pressurizer [10]. The simplified bench consists of two 200-liter volume tanks, where the boration and dilution process happen, a dose pump, a frequency counter, two rotameters for the outflow measurement, stainless accuracy valves, brass sphere valves, connections and tubes with a 3/8" intern diameter in stainless steel, as shown in Fig. 3 [10].

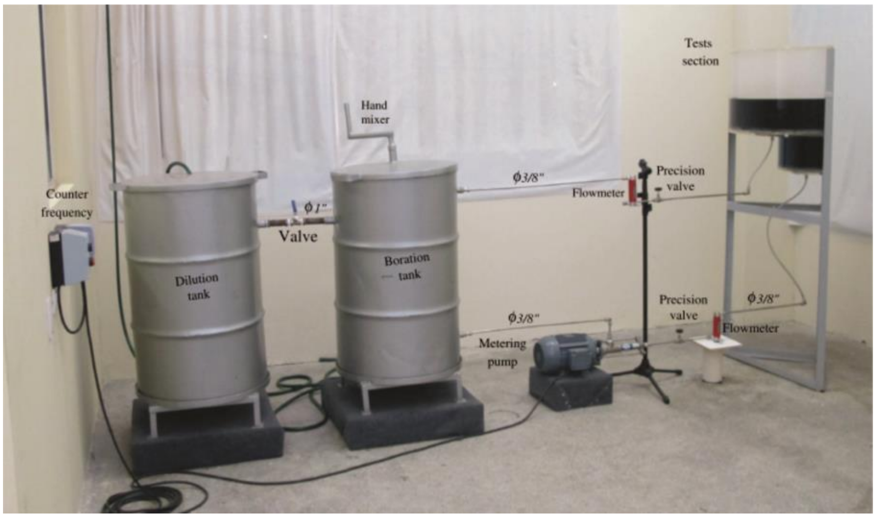


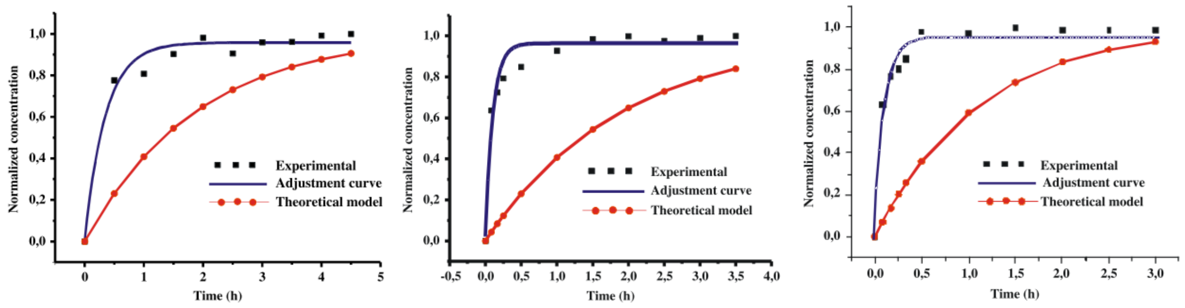
Figure 5: Experimental set [12].

In the execution of the experiments, a dye with properties similar to boric acid was used to allow visualization. The data referring to the experiments carried out in this preliminary study are shown in Table 4.

Table 4: Data referring to the experiments [11]

Experiment	Power (%)	Concentration (ppm)	Test section (l)	Boration tank (l)	Orifice diameter (mm)
A	100	100	40.5	100	10
B	20	400	40.4	100	10
C	0	1000	17.0	100	10

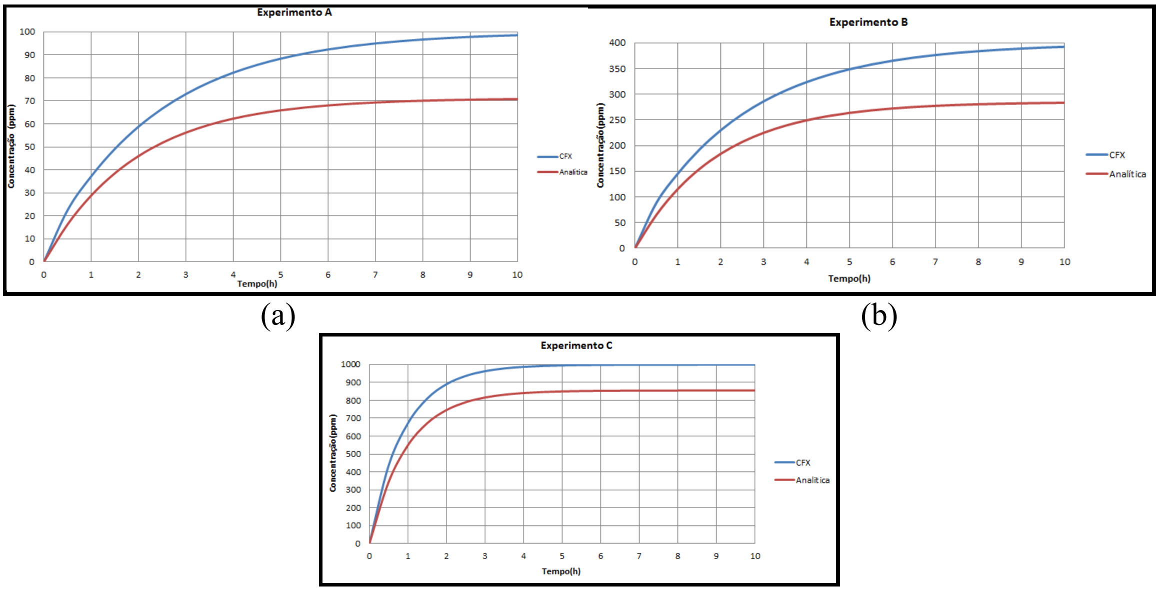
In this study, digital images of the test section were obtained during the homogenization process. The evolution of the dye plume in the TS was registered at every 30 min, during a time of approximately 5 h, when there was a visual indication of the homogenization of the dye in the system. The images obtained were processed with the DIP (Digital Image Processing) program [12]. The results obtained with DIP made it possible to quantify the value of the concentration of dye through time in the tests section. In Fig. 6, it is possible to see that the curve of the theoretical model shows also that in this time the homogenization of the system tends to stabilize.



(a) (b) (c)

Figure 6: Normalized concentration x time (a) Experiment A, (b) Experiment B and (c) Experiment C [12].

Later, by using a commercial Computational Fluid Dynamics program (CFX), these three examples were simulated by using different operating conditions enabling to evaluate the parameters that could influence this homogenization. Case studies such as variation of the dimensions of the water inlet and outlet tubes, flow variation and change in positioning of entrances and exits were made with the goal of finding parameters that could help the optimization of the homogenization of boron [13]. The Fig. 7 illustrates the comparison for the experiment "A, B and C" between the analytical solution of the model used in the experiment and the solution found by the simulation in CFX.



(a) (b)

(c)

Figure 7: CFX results and analytical results - Concentration x time (a) Experiment A, (b) Experiment B and (c) Experiment C [13].

The same asymptotic behavior of the curves is observed, which tend to a maximum concentration value. The difference between the values found by experimental model using the CFX can be related to the fact that the analytical solution does not take into account the geometry of the problem. The homogenization in both cases occurs approximately after 5 hours [13].

3. CONCLUSIONS

This paper reports the description of the test facility under construction at CRCN/NE (Brazil), its features and status of its realization. The development of this low-pressure facility will provide the necessary structure to study, on an adequate scale, boron transients in pressurizer of SMR with integral configuration (iPWR). It highlights also its capability of being suitable for others studies of boron homogenizing process in the pressurizer of an integral modular nuclear reactor of different design.

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