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NEW SIGNAL ACQUISITION AND PROCESSING SYSTEM FOR THE EXECUTION OF INITIAL CRITICALITY AFTER REFUELING AND PHYSICAL TESTS AT LOW POWER IN ANGRA 2, WITH THE INCORPORATION OF THE REAL TIME RESOLUTION OF THE INVERSE POINT KINETIC EQUATION – IPK

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ABSTRACT

The goal of this work is present the new System of Acquisition and Signal Processing for the execution of the initial criticality after refueling and physical tests at low power with the incorporation of the real time resolution of Inverse Point Kinetic Equations (IPK). The system was developed using cRIO 9082 hardware (compactRIO), which is a programmable logic controller (PLC) and, the National Lab's LabVIEW programming language. The developed system enabled a better visualization and monitoring interface of the neutron flux evolution during the first criticality of cycle and following the low power physical tests, which allows the Reactor Physics Group and Reactor Operators of Angra 2 guide faster and accurately the reactivity variations at physical tests. The digital reactivity meter developed reinforces in Angra 2 the set of operational practices of reactivity management.

1. INTRODUCTION

The purpose of the physical tests performed on the start-up after recharging the reactor core refueling is to demonstrate that the new core performs according to the design parameters of reactor project [1]. The comparison of the measured/ calculated values is performed for the following reference conditions: hot zero power (HZP), free of xenon and hot full power (HFP), xenon in equilibrium. For the given reference conditions [2], the core verification are based on the following comparisons:

- Measured/calculated values of critical boron concentrations (boric acid) – C_b for selected control bar configuration.
- Activation rates used as measure of neutron flux distribution and comparison with calculated data, and comparison of measured/calculated boron concentration.

In order to estimate the validity of the core design bases in the case of a significantly higher than expected reactivity, it is necessary to know the discrepancies between measurements and predictions in both conditions mentioned above.

The relevant parameter that influences the reactivity balance, therefore the shutdown margin [3], is the boron equivalent reactivity, which corresponds to the transition of full power with xenon in equilibrium, to zero power, free of xenon. This parameter is expressed as: boron equivalent by the difference between the critical concentration of boron (C_b) to HZP, free of xenon, all control rods out (ARO) and critical concentration of boron at hot full power (HFP), xenon in equilibrium, control bars in the demand position. If this boron equivalent reactivity is greater than the predicted value, the shutdown margin is affected turning the temperature coefficient less negative, ultimately, diminishing in this way the inherent safety of the plant.

The procedure to startup Angra 2 after core's refueling, 2PIR008 - Initial Criticality After Refueling and Physical Tests at Low Power [4], uses the boron end point methodology [5], which consists in letting the reactor close to the criticality ($\rho = 0$), at zero power, without generating nuclear heat and performing the measurements of the critical boron concentrations the following settings: Cb_o - ARO and Cb_x - a group of fully inserted control rods and compare the result with the project data. In this procedure it is also required that an Extra System of Acquisition and Signal Processing has been installed and tested in the control room.

The main parameters monitored by the extra monitoring system are: the neutron flux of the intermediate power range - FI(A) and its derivative signal, represented by the relative variation of the neutron flux - Inverse of the Period 1/T (% /sec). Through the slope of the FI curve or the value of 1/T, it is possible to indicate to the reactor operators, in small steps, the determine the movement direction of control rods or the total amount of boron/demineralized water to be inserted into the reactor cooling system (SRR), as well as verify its effects on the neutron flux, in order to let the reactor near criticality.

The Extra System for Acquisition and Signal Processing currently used is obsolete. In order to replace it, the cRIO 9082 hardware (compactRIO) [6], which is a modular programmable logic controller (PLC) with digital and analog inputs and outputs, was purchased from the National Instruments Company using the LabVIEW/RT (Real Time) operating system [7].

For the development of the graphical interface LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) software [8] was used. The system developed in LabVIEW enabled an improvement in the visualization and monitoring interface of the evolution of the neutron flux during the low power physical tests of Cycle 13. The development of a function (subroutine) for the real-time resolution of IPK [9,10] allowed to the real-time quantification and visualization of reactivity.

Reactivity Management, according to WANO SOER 2007-1 - Reactivity Management [11], is related to the philosophy of operation of power reactors and specific guidelines applied to the control of conditions that affect reactivity. This includes that all activities related to core reactivity control and stored nuclear fuel (where potential for criticality may occur) are monitored and controlled according to operational limits and fuel design. This is a key factor in ensuring the integrity of barriers to preclude release of fission products.

The real-time knowledge of the reactivity value allows Reactor Physics Group of Angra 2 orient the Reactor Operators more fast and accurately on the positioning of the control rod banks, or in determination of the total boron or demineralised water to be inserted in the reactor coolant system (RCS) to carry the neutron chain reaction nearly criticality condition (without power variation), necessary condition to perform the measurements of the required critical boron concentrations. In this way, the developed system reinforces in Angra 2 the set of operational practices of Reactivity Management.

2. NEW SYSTEM FOR ACQUISITION AND PROCESSING OF SIGNALS FOR PHYSICAL TESTS AT LOW POWER.

It was used the hardware cRIO 9082 connected to panel of test computer CWX01 located in the in the left side of main control room, Figure 1, with the following configuration:

- 1 Power supply,
- cRIO-9082 controller with 1.33 GHz dual-core CPU,
- 2 modules of the C-9229 Series of analog input with 4 channels, 24 bits,
- 1 Series C-9401 5 V / TTL, Bidirectional Digital I / O, 8 Ch,
- 1 operating system - LabVIEW - Real Time (RT).

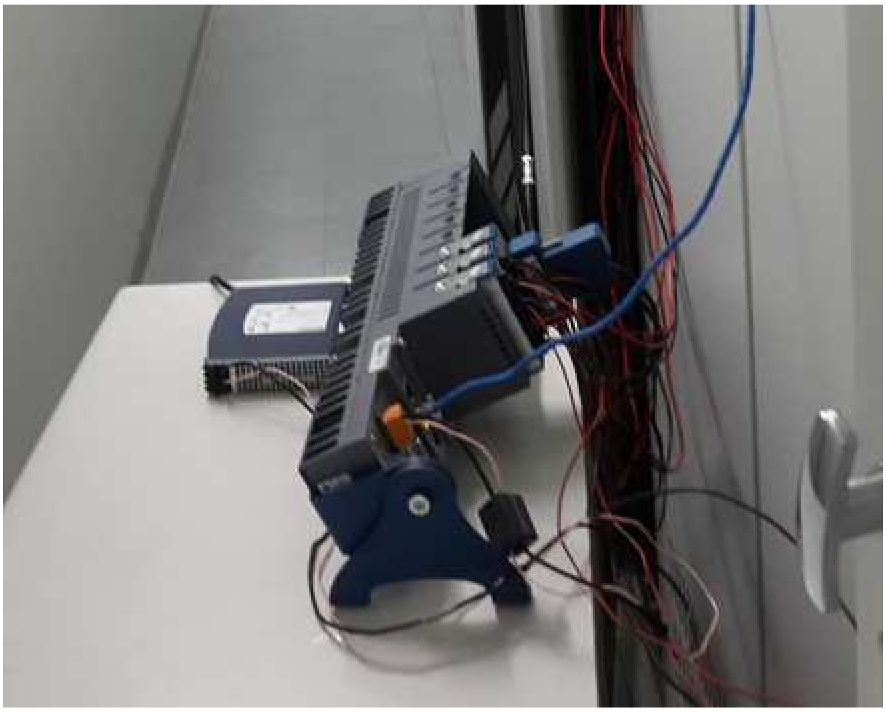


Figure 1: CWX Panel of test computer - cRIO 9082 controller in use during cycle 13 physical tests.

The cRIO-9082 is a PLC with digital and analog inputs and outputs for the acquisition and processing of instrumentation signals from the Plant using the LabVIEW/RT operating system. The eight analog channels and the 2 digital channels of the cRIO-9082 modules C-9229/C-9401 were connected, via temporary cabling, to the respective terminals of the CWX01 enclosure. In this case, it is possible to read the signals from most sensors used in the Plant. The electrical signals in the 0 to 1 volt measuring range from the plant sensors and available in the respective terminals of the CWX01 cabinet were collected through modules C-9229/C-9401 of the cRIO-9082 device. The following process variable was recorded:

- Reactor Input Temperature: 0-400° C
- Reactor Output Temperature: 0-400° C
- Primary System Pressure 2nd Maximum: 0-180 bar
- Intermediate Power Range: $10E^{-11}$ - $5x10E^{-5}$ A
- Relative Variation of Neutron Flow (Inverse Period): 0-10%/s
- Mass Flow of Boric Acid: 0-16 kg / sec
- Demineralized Water Flow: 0-26 kg / sec
- 2° Maximum of Position Bank L: 0-400 cm

The LabVIEW has been installed on a development computer (Host). The cRIO-9082 (Target) was connected to this computer byt an ethernet standard twisted-pair cable. A private computer network was established between the cRIO9082 and the development computer using TCP/IP (Transmission Control Protocol/Internet Protocol) protocols, Figure 2. LabVIEW is a platform environment and development of a visual programming of graphical language from National Instruments called G.

In the LabVIEW is commonly used for data acquisition, instrument control, and industrial automation. The code files have the extension .vi, abbreviated to Virtual Instrument (VI), because their appearance and form of operation imitate bench instruments such as multimeters, oscilloscopes, etc.

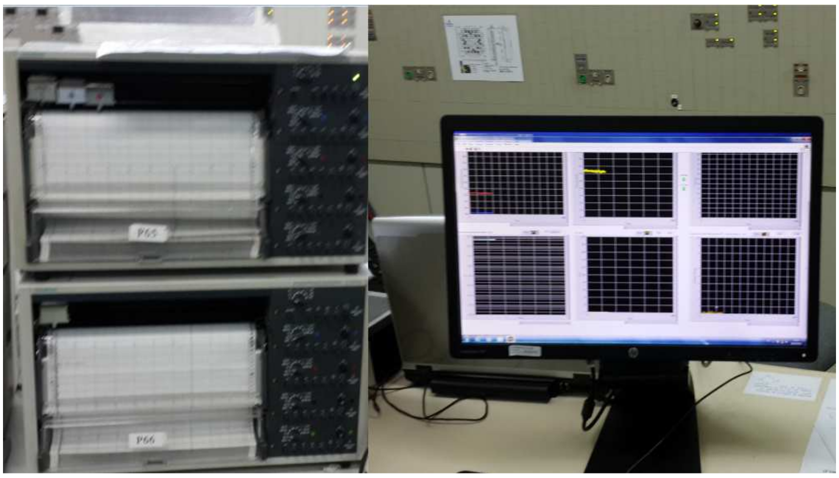


Figure 2: Strip chart of old system acquisition and Front Panel of the new system, during the cycle 13 physical tests.

In labVIEW the user interface is built through a screen in the program called Front Panel, and with the aid of objects that are inserted through the drag-and-drop operation of a tool panel, associated to each Front Panel there is a screen, created automatically in the program, called Block Diagram, which is used for the edition and execution of the VI.

In the tests of cycle 13, a frequency of 20 Hz was used to perform the loops, that is, the instrumentation signal readings, also called sampling time (Ta), as well as all data processing were executed with the period of 50 ms (milliseconds). In an on-line measurement/ monitoring device of physical quantities of the Plant, it is necessary to automatically multiply the electrical signals coming from the sensors of this device by a constant or equivalent function. Figure 3 shows the block diagram developed, where the eight signals collected by the C-9229 modules in voltage, plus the two signals collected from the C-9401 module in number of pulses, are transformed into engineering units.

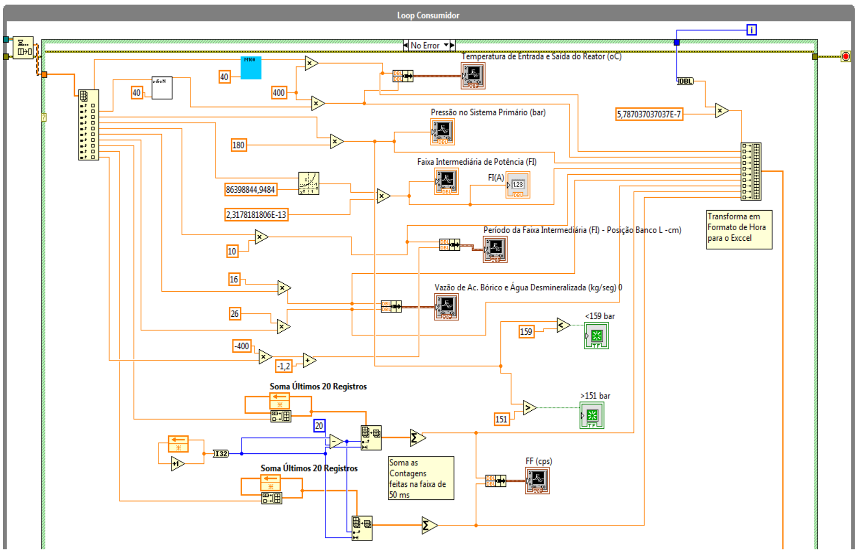


Figure 3: Block Diagram where the eight analog signals collected by the C-9229 modules in voltage, plus the two signals collected from the C-9401 module in number of pulses, are transformed into engineering units.

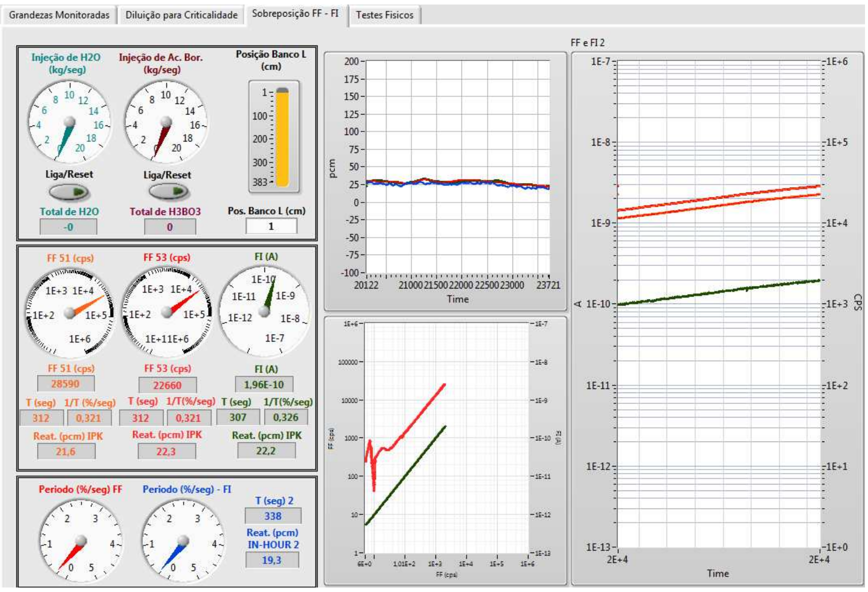
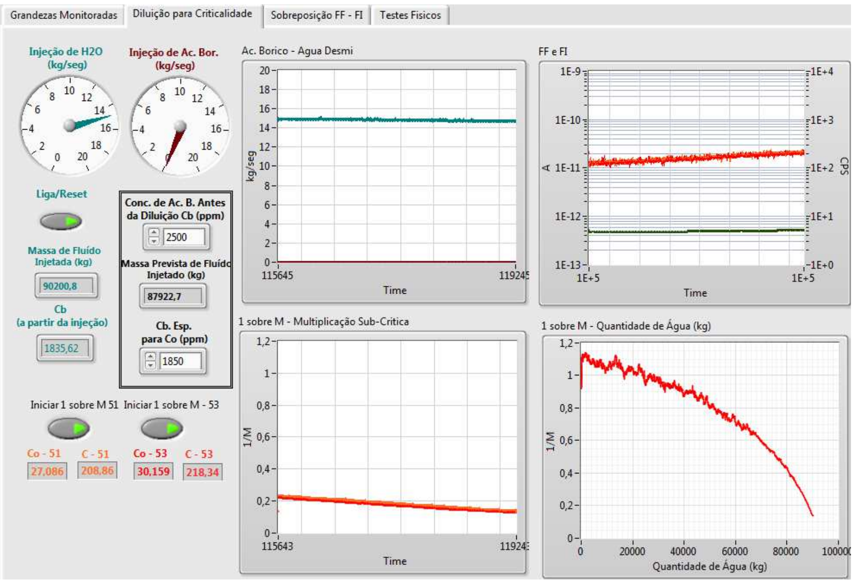


Figure 4: Front Panel of the extra monitoring system developed showing the best visualization interface of the evolution of the neutron flux during the FF-FI overlap test.

In the developed system several files of Front Panel were created, where it was possible, through indicators and graphs (charts), to verify the real-time evolution of the physical quantities monitored. The developed system allows a better visualization interface of the neutron flux evolution during: Initial Criticality (real-time 1/M curve, Figure 4), FF/FI

Overlap Test (FF and FI, in a single graph, Figure 5) and physical tests during the execution of the steps of the 2PI-R08 procedure.



Massa de Fluído Injetada (kg) 90200,8

Cb (a partir da injeção) 1835,62

Conc. de Ac. B. Antes da Diluição Cb (ppm) 2500

Massa Prevista de Fluído Injetado (kg) 87922,7

Cb. Esp. para Co (ppm) 1850

Co - 51 27,086

C - 51 208,86

Co - 53 30,159

C - 53 218,34

Figure 5: Front Panel of the initial criticality monitoring extra system (1/M curve in real time).

3. KINETICS OF REACTORS AND PHYSICAL TEST

3.1. Reactor Kinetic

In the analysis of the behavior of the population of neutrons in relation to the time in a nuclear reactor, we consider the multiplication factor K of the medium, which is effectively the number of neutrons present at the end of a generation of neutrons for each neutron present at the beginning of this generation. The variation of the flux $\Delta\Phi$ can be written as $\Delta\Phi = (K-1)\Phi$, therefore, during the lifetime of the neutron ℓ, the neutron flux Φ varies by multiplication factor k, and the variation index $d\Phi/dt$ can be written as follows:

$$\frac{d\Phi}{dt} = \frac{K-1}{\ell}\Phi \quad or \quad \frac{d\Phi}{dt}\frac{1}{\Phi} = \frac{\dot{\Phi}}{\Phi} = \frac{K-1}{\ell} = \frac{1}{T} \qquad (1)$$

Where T is the reactor period and 1/T is the inverse of the period (and also the relative variation index of the neutron flux Φ'/Φ). The period T is defined as the time required for the reactor power to change from an "e" factor, where "e" is the basis of the natural logarithm. In the resolution of equation (1) we have:

$$\Phi(t) = \Phi_0 e^{\frac{K-1}{\ell}t} \; or \; \Phi(t) = \Phi_0 e^{\frac{1}{T}t} \; or \; P(t) = P_0 e^{\frac{1}{T}t} \qquad (2)$$

Where:

P = Reactor Power
Po = Initial reactor power
Φ = Neutron flux of the reactor at a given instant (Proportional to Reactor Power)
Φ_o = Neutron flux of the reactor at an initial time t = 0 (Proportional to P_o)
T = Period (seconds)
t = Time the reactor takes to reach Φ or P
ℓ = Lifetime of a neutron

3.2 Determination of Reactivity

Reactivity is the most important parameter in nuclear reactors, and in nuclear plant projects this information can be used for further investigations of design bases of many plant systems that are related to reactor operation. Real-time indication of reactivity is important from the point of view of shutdown margin monitoring, calibration of control and safety devices, detection of any inadvertent insertion of core reactivity, restriction of reactivity control range, etc.

The Point Kinetics Equation of the Reactor is a system with seven nonlinear coupled ordinary differential equations describing the evolution in time of the neutron distribution and the concentration of delayed neutron precursors in the core of a nuclear reactor, indicated by:

$$\frac{dP}{dt} = \left(\frac{\rho - \beta}{\ell}\right) P + \sum_{i=1}^{m} \lambda_i \, C_i + S \tag{3}$$

$$\frac{C_i}{dt} = \frac{\beta_i}{\ell} - \lambda_i C_i \tag{4}$$

where:

- ρ is the reactivity;
- ℓ is the lifetime of a neutron (sec)
- P is the power of the reactor proportional to the neutron flux;
- Ci is the contraction of the i^{th} group of delayed neutron precursors (atom /cm3);
- i is the group of delayed neutron precursors (sec^{-1}), where i = 1.2..6);
- β_i is the effective fraction of the i^{th} group of delayed neutron precursors;
- λ_i is the decay constant of the i^{th} group of delayed neutron precursors;

The source term S was considered zero, once the reactivity calculus was made near the criticality. The values of ℓ, λ_i and β_i was taken of Final Core Design Report of Cycle 13 [1], Table 1.

3.4 In-Hour Equation

One of the solutions of point kinetics equation is the well-known In-Hour function (5), already used in the first nuclear reactors and obligatorily used in the initial training of nuclear reactor operators:

$$\rho = \frac{\ell}{T.K} + \sum_{i=1}^{6} \frac{\beta_i}{1 + \lambda_{i.}T} \tag{5}$$

The first term of the function is the term related to the prompt neutrons and the second term is the term related to the delayed neutrons. The In-Hour equation represents the ratio of the increase of reactivity with the stable or asymptotic period of the reactor.

Table 1: Angra 2/Cycle 13 – Delayed Neutron Data

Group i	λi (1/seg)	βi (%)
1	0,0128	0,0193
2	0,0316	0,1240
3	0,1215	0,1120
4	0,3224	0,2399
5	1,4035	0,0894
6	3,8567	0,0219
ℓ (micro-seg)	17,19	

3.5 On-line Resolution of Inverse Point Kinetics Equation (IPK)

A Digital Reactivity Meter consists of a computational system for calculating reactivity. The most common method used in digital reactors is the inverse point kinetics equation (IPK). From equations (3) and (4) the following equation can be obtained:

$$\rho = \frac{\ell}{T} + \left(\frac{dP}{dt} + \sum_{i=1}^{m} \frac{dC_i}{dt} \right) \tag{6}$$

In general, it is convenient to treat discrete dynamic models instead of continuous ones, because the quantities that come from real observations are discrete. If the reactor power samplings (measurements) are made available as P_k, at a time k * (T_a) on k = 0,1,2,3,4,5 ... where (T_a = dt) is the sampling interval (or sample time). Then, the derivatives of equation (6) can be approximated by:

$$\frac{dP}{dt}_k = \frac{P_k - P_{k-1}}{T_a} \quad and \quad \frac{dC_i}{dt}_k = \frac{C_{i,k} - C_{i,k-1}}{T_a} \tag{7}$$

Equation (4) can also be deduced by:

$$C_{i,k} = e^{-\lambda_i T_a} C_{i,k-1} + \frac{1}{\lambda_i}\left(1 - e^{-\lambda_i T_a}\right)\frac{\beta_i}{\ell} P_k \tag{8}$$

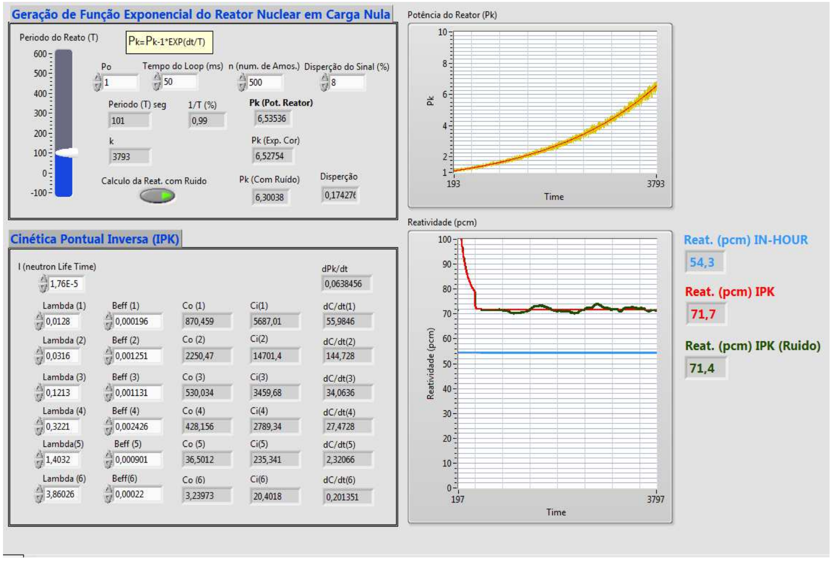
Then substituting (7) into (6), we have:

$$P_k = \frac{\ell}{P_k}\left(\frac{P_k - P_{k-1}}{T_a} + \sum_{i=1}^{m} \frac{C_{i,k} - C_{i,k-1}}{T_a}\right) \tag{9}$$

Equations (8) and (9) are easily implemented in a digital computer, and will give estimates of reactivity at different time instants from the power history P_k, in a constant sampling interval (T_a = dt).

3.6 In-Hour and IPK in LabVIEW

In order to test and compare the In-Hour and IPK functions, a VI was developed in the system in which equation (2) was adapted to generate the simulation of the operation of a nuclear reactor at zero load. As a result, a power history can be formed as follows: **P_k = P_{k-1} * exp (dt /T), k = 0,1,2,3,4,5 ...** where: Po is the initial power, dt is the time interval between P_k and P_{k-1} and T the reactor period. Figure 6 shows the Front Panel of this VI and Figure 7 shows part of the Block Diagram.



Geração de Função Exponencial do Reator Nuclear em Carga Nula

Pk=Pk-1*EXP(dt/T)

Periodo do Reato (T)

Po: 1
Tempo do Loop (ms): 50
n (num. de Amos.): 500
Disperção do Sinal (%): 8
Periodo (T) seg: 101
1/T (%): 0,99
Pk (Pot. Reator): 6,53536
k: 3793
Pk (Exp. Cor): 6,52754
Calculo da Reat. com Ruido
Pk (Com Ruído): 6,30038
Disperção: 0,17427

Cinética Pontual Inversa (IPK)

l (neutron Life Time): 1,76E-5
dPk/dt: 0,0638456

Lambda	Beff	Co	Ci	dC/dt
Lambda (1): 0,0128	Beff (1): 0,000196	Co (1): 870,459	Ci(1): 5687,01	dC/dt(1): 55,9846
Lambda (2): 0,0316	Beff (2): 0,001251	Co (2): 2250,47	Ci(2): 14701,4	dC/dt(2): 144,728
Lambda (3): 0,1213	Beff (3): 0,001131	Co (3): 530,034	Ci(3): 3459,68	dC/dt(3): 34,0636
Lambda (4): 0,3221	Beff (4): 0,002426	Co (4): 428,156	Ci(4): 2789,34	dC/dt(4): 27,4728
Lambda(5): 1,4032	Beff (5): 0,000901	Co (5): 36,5012	Ci(5): 235,341	dC/dt(5): 2,32066
Lambda (6): 3,86026	Beff(6): 0,00022	Co (6): 3,23973	Ci(6): 20,4018	dC/dt(6): 0,201351

Reat. (pcm) IN-HOUR: 54,3
Reat. (pcm) IPK: 71,7
Reat. (pcm) IPK (Ruido): 71,4

Figure 6: Front Panel of the exponential function simulator of the reactor to test the sub-VI of calculation of the reactivity by In-Hour and IPK.

The development of the functions of In-Hour, equation (5), Figure 8, and IPK in LabVIEW, equations (8) and (9), was done through sub-VIs (subroutines), which could be used in other VIs of the program, Figures 8 and 9. For the function tests, a simulation was performed, where the value of the Reactor Period (T) was set at levels of 25, 50, 100, 200, 300, 400, 500 and 600 seconds. The results of these simulations are presented in Table 2.

The reactivity equivalent reactivity values calculated by In-Hour and IPK practically coincided for the long reactor periods, and the reactivity value calculated by IPK showed to be more conservative for short reactor periods. In the Physical Tests of Cycle 13, a history with the monitored variables was generated in MS /EXCEL with the same acquisition rate of the 0.05 second loops, for a total of 434,941 lines, corresponding to approximately 6 hours of data. With this file it was possible to create a VI, for analysis and processing of the variables monitored as if the data were being obtained online by the instrumentation sensors, Figure 10.

Table 2: Simulation of Reactivity as a Function of the Inverse of Period

T (seg)	**1/T** (%/seg)	**In-Hour** (pcm)	**IPK** (pcm)
25	4.000	141	289
50	2.000	91	145
100	1.000	55	72
200	0.500	31	36
300	0.333	22	25
400	0.250	16	18
500	0.200	13	14
600	0.167	11	11

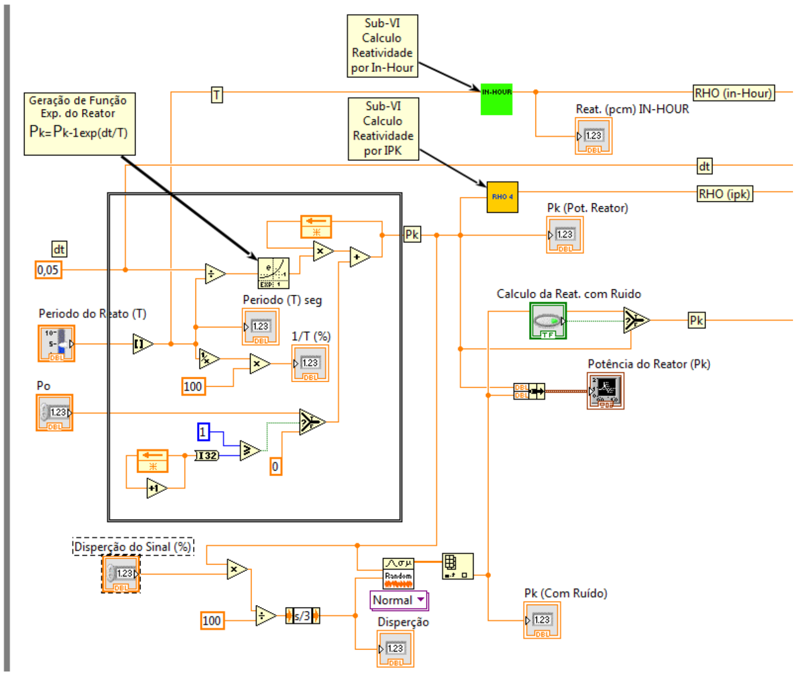


Figura 7: Block Diagram of the exponential function simulator for the sub-VIs of reactivity calculation by In-Hour and IPK.

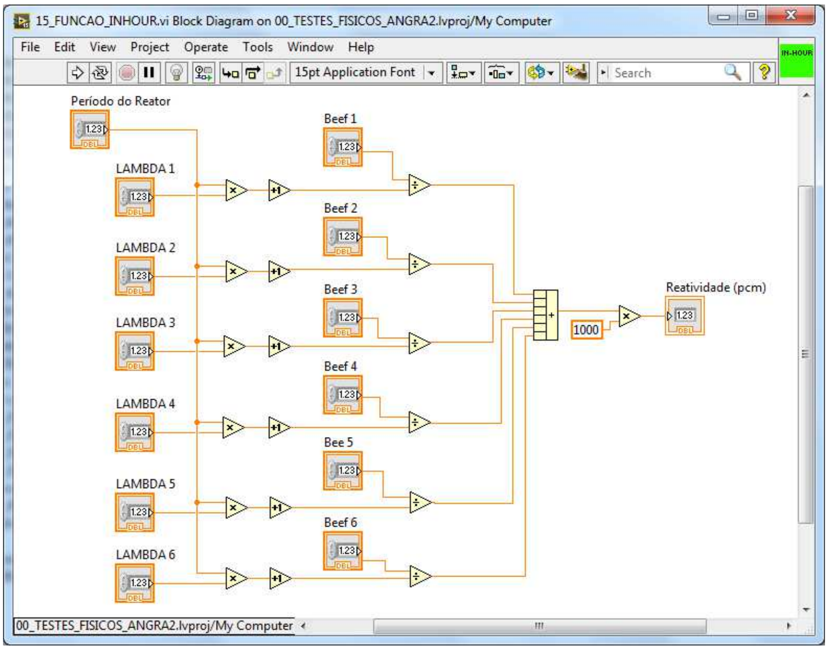


Figure 8: Block Diagram of the In-Hour Reactivity alculation Sub-VIs.

To determine online the reactivity parameters of the core in the physical tests (sub-VIs) were developed for the real-time realization of the Reactivity Balances that enabled the automatic determination of the positioning of the control banks L, Figure 11, and/or for the determination of the total mass quantities of boron acid or demineralized water. This data allows to know quickly the values this to bring the reactor to criticality condition (ρ = 0). As explained before, this condition is necessary to carry out the Boron Critical Concentrations (Cb) measurements in the control rod configurations required in the low power physical tests af Angra 2.

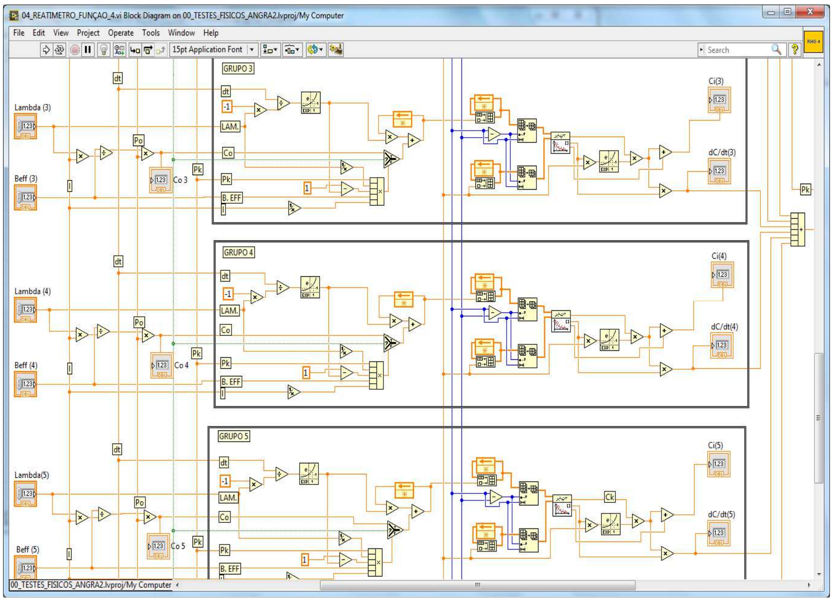
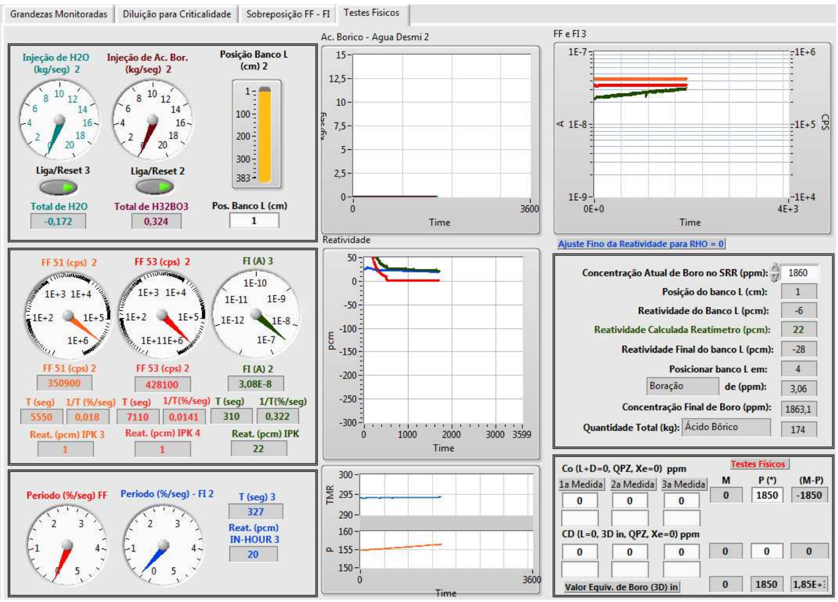


Figure 9: Block Diagram of the Sub-VI to calculate reactivity by IPK.

Also, functions were created, sub-VIs, for the determination of the total quantities of Boron or Water mass inserted in the primary circuit, through the integration of Boric Acid Mass Flows (kg/sec) or Demineralized Water Mass Flow / Sec), indications that were previously only available on the control panel of the reactor operator.



Total de H2O: -0,172
Total de H32BO3: 0,324
Pos. Banco L (cm): 1

FF 51 (cps) 2: 350900
FF 53 (cps) 2: 428100
FI (A) 2: 3,08E-8

T (seg)	1/T (%/seg)	T (seg)	1/T(%/seg)	T (seg)	1/T(%/seg)
5550	0,018	7110	0,0141	310	0,322

Reat. (pcm) IPK 3: 1
Reat. (pcm) IPK 4: 1
Reat. (pcm) IPK: 22

T (seg) 3: 327
Reat. (pcm) IN-HOUR 3: 20

Concentração Atual de Boro no SRR (ppm): 1860
Posição do banco L (cm): 1
Reatividade do Banco L (pcm): -6
Reatividade Calculada Reatímetro (pcm): 22
Reatividade Final do banco L (pcm): -28
Posicionar banco L em: 4
Boração de (ppm): 3,06
Concentração Final de Boro (ppm): 1863,1
Quantidade Total (kg): Ácido Bôrico 174

Co (L+D=0, QPZ, Xe=0) ppm					
1a Medida	2a Medida	3a Medida	M	P (*)	(M-P)
0	0	0	0	1850	-1850
CD (L=0, 3D in, QPZ, Xe=0) ppm					
0	0	0	0	0	0
Valor Equiv. de Boro (3D) in			0	1850	1,85E+:

Figure 10: Front Panel for processing the monitored variables online by the instrumentation sensors in the Physical Tests of Cycle 13.

4. CONCLUSIONS

The implementation of the new extra system for acquiring and processing signals for low-power physical testing through the use of the integrated hardware/software platform from national instruments will effectively replace the old system that is obsolete. The system also allows its expansion for use in all modes of operation of the plant.

The developed system enables a better visualization and monitoring interface of the neutron flux evolution during the low power physical tests, which allows Reactor Physics Group to guide Reactor Operators more quickly and accurately in the reactivity variations. The construction of the Digital Reactivity Meter was configured by implementing the function of the Inverse Kinetic Equation (IPK) of the reactor power, reinforcing the set of operational practices of Reactivity Management in Angra 2.

5. ACKNOWLEDGEMENT

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