2011 International Nuclear Atlantic Conference - INAC 2011
Belo Horizonte,MG, Brazil, October 24-28, 2011
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: **978-85-99141-04-5**

DEVELOPMENT OF A NUCLEAR REACTOR CONTROL SYSTEM SIMULATOR USING VIRTUAL INSTRUMENTS

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ABSTRACT

The International Atomic Energy Agency recommends the use of safety and friendly interfaces for monitoring and controlling the operational parameters of the nuclear reactors. This article describes a digital system being developed to simulate the behavior of the operating parameters using virtual instruments. The control objective is to bring the reactor power from its source level (mW) to a full power (kW). It is intended for education of basic reactor neutronic and thermohydraulic principles such as the multiplication factor, criticality, reactivity, period, delayed neutron, control by rods, fuel and coolant temperatures, power, etc. The 250 kW IPR-R1 TRIGA research reactor at Nuclear Technology Development Centre - CDTN was used as reference. TRIGA reactors, developed by General Atomics (GA), are the most widely used research reactor in the world. The simulator system is being developed using the LabVIEW® (*Laboratory Virtual Instruments Engineering Workbench*) software, considering the modern concept of virtual instruments (VI's) using electronic processor and visual interface in video monitor. The main purpose of the system is to provide training tools for instructors and students, allowing navigating by user-friendly operator interface and monitoring tendencies of the operational variables. It will be an interactive tool for training and teaching and could be used to predict the reactor behavior. Some scenarios are presented to demonstrate that it is possible to know the behavior of some variables from knowledge of input parameters. The TRIGA simulator system will allow the study of parameters, which affect the reactor operation, without the necessity of using the facility.

1. INTRODUCTION

The instrumentation of nuclear reactors are designed with the principle that reliability, redundancy and diversification of control systems. The reliable monitoring of the parameters involved in the chain reaction is of crucial importance with regard to efficiency and operational safety of the installation. In the reactor IPR-R1 TRIGA operational variables are shown on analog indicators located on the control console. The operators register the most important parameters of the operation manually. The control console uses discrete electronic components and logic of the operation is performed by relays. The CDTN intends to adopt in their laboratories to ISO (International Organization for Standardization), to show reliability in the results [1]. According to ISO 9000, an institution must attend to certain requirements to be certified. Among these, one can mention: measuring and monitoring processes to ensure the quality of the product / service through performance indicators and deviations; implement and maintain appropriate and necessary records to ensure traceability of the process and conduct systematic reviews of processes and of the quality system to ensure its effectiveness.

A digital system being developed to simulate the behavior of the IPR-R1 TRIGA reactor operational parameters. In addition to simulate the system can be used to monitor, in real time, the parameters using the modern concept of virtual instruments with visual interfaces in video monitors. The data from all operations could be collected by the computer and could be available for treatment, analysis and monitoring. The system can also be used for simulation of the operation, assisting in the knowledge of the behavior of the operating variables. The realization of this work will contribute to the use of the IPR-R1 in research and training, in addition to meeting the recommendations of the International Atomic Energy Agency (IAEA), who has encouraged its members to develop strategic plans for use of research reactors, beyond recommendations on the modernization of the instrumentation in order to ensure safe operation [2].

2. THE IPR-R1 TRIGA RESEARCH REACTOR

The TRIGA reactors (Training Research Isotope General Atomics) are the most used research reactors in the world. There are, currently, 65 reactors of this type in operating installed in 25 countries. The company General Atomics (GA), manufacturer of TRIGA reactors, since the late 50's, continues to design and install these reactors. They are built in various configurations and power ranging from 100 kW to 16 MW. The IPR-R1 TRIGA reactor, shown in Fig.1, is used for chemical analysis by neutronic activation and, to a lesser extent, for research and training. Its first criticality was in 1960 with a maximum thermal power of 30 kW. In the 70’s fuel elements were added in the core increasing power to 100 kW, which is the current maximum licensed power. In 2002, were started theoretical and experimental research to know its neutronic behavior and allow their operation at 250 kW [3] [4]. On that date, changes were made in the core, were added new fuel elements, allowing the power reach 250 kW and studies were initiated to know the mechanisms of heat transfer in this level of power [5] and [6].

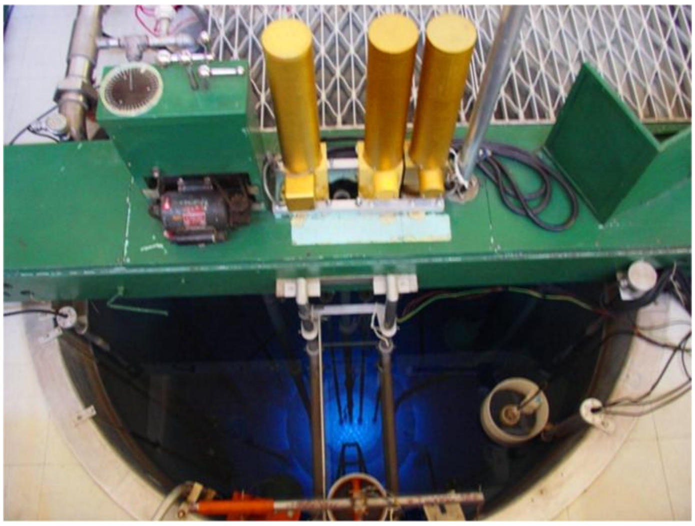

Figure 1. The IPR-R1 TRIGA Research Reactor

Currently there are in the IPR-R1 reactor core 63 cylindrical fuel elements. The fuel is an alloy of zirconium hydride (neutrons moderator) and uranium enriched to 20% in ^{235}U. The reactor power is controlled by three independent control rods. The two main power measure channels are the Logarithmic Channel and the Linear Channel which consist of ionization chambers sensitive to neutron flux, installed around the core. Both channels are designed so as to monitor the neutron flux evolution, with the same accuracy since some mW until the maximum power of 250 kW. It was developed a data acquisition system to support the realizations of the experiments of heat transfer [6]. This system, due to great progress in electronics and computing, is already obsolete and has some limitations.

3. VIRTUAL INSTRUMENTS (VI)

The proposed system will be developed using the LabVIEW® software (Laboratory Virtual Instruments Engineering Workbench). This program uses the modern concept of virtual instruments (VI's), microprocessors and using visual interface on video monitors [7]. The icons in the LabVIEW® represent the controls and functions available in the menus of the software, called visual programming. The LabVIEW® breaks the paradigm of programming language-based text to an icon-based programming. The user interface consists of two parts, which are: the front panel and the block diagram, similar to traditional instruments, which have a front panel and the printed circuit board on which is the electronic circuit. On the front panel of LabVIEW® can be created the control buttons, keys, LED indicators and graphical displays to present the data, while in the in the block diagram reside the blocks who, properly interconnected, constitute the electronic circuit.

4. JUSTIFICATION

The International Atomic Energy Agency recommends the control rooms update of nuclear reactors [8] [9], [10] and [11]. In the IPR-R1 some operating variables are not monitored, especially some thermal-hydraulic parameters important for operation at 250 kW. The undergraduate and postgraduate students and the reactor operators do not find a control system in IPR-R1 reactor of the same type adopted by nuclear centers or even in the industries. The new systems are based on microprocessors and use friendly human-machine interface typical of today's control rooms. The instrumentation of nuclear reactors is designed based on reliability, redundancy and diversification of control systems. The monitoring of the parameters is of crucial importance with regard to efficiency and operational safety of the installation. Since the first criticality of a nuclear reactor, achieved by Fermi and collaborators in 1942, there has been concern about the reliable monitoring of the parameters involved in the chain reaction.

The system proposed here for operational variables monitoring and simulation of the flow of neutrons and their interaction on the other operational parameters is in development and will be validated experimentally in the research reactor TRIGA IPR-R1. The innovations developed in research reactors are usually used in power reactors. The relative low costs allow to the research reactors be an excellent laboratory for the development of techniques for future reactors [12]. The operation of nuclear reactors involves mainly the neutronic (physics neutron) and thermal-hydraulic (heat transfer and fluid dynamics). The dynamic behavior of the reactors is associated with an important property known as reactivity. This property varies with the temperature change of the fuels [13].

The existence of a passive system that indicates that the reactor is turned off is a recommendation of the IAEA [20]. The IPR-R1 Safety Analysis Report predicts the existence of a supervisory system powered by "no-break" receiving signals from thermocouples located inside the fuel element ("self-powered" sensors). So the shutdown of the reactor by a power outage may be confirmed by the operator [14].

5. OBJECTIVES

The main objective is to provide the IPR-R1 TRIGA research reactor of a modern and reliable digital system for simulating its operational parameters covering its entire operating range (0 to 250 kW). The system will be validated comparing to actual operating data. As a secondary goal of the work can be cited the implementation of instrumentation for monitoring of parameters not currently monitored in the facility, including: internal temperature of the fuel, electrical conductivity and pH of the water of the primary in function of temperature, radiation level of the control room, the flow of the secondary circuit, system for the visual monitoring of the core, etc.

6. METHODOLOGY

The basic principles and the instrumentation related to the operation of nuclear reactors, which will be simulated and monitored by the system is present here.

6.1 Nuclear Reactors Kinetics and Control

The importance of nuclear fission, from the point of view of its use in power generation, is due to three factors. First, the process is associated with the release of a large amount of energy per unit mass of fuel. Second, fission reactions, which are initiated by neutrons are accompanied by the release of an average of 2.5 new neutrons (fission of ^{235}U). Third, the fact that some neutrons generated in fission only appear with some delay after the fission, causing the growth rate will suffer a great reduction, enabling the control of the reaction. The combination of these factors enabled the design of nuclear reactors, in which the chain reaction is sustainable with the continuous and controlled release of energy [15].

For the delayed neutron fraction is used the β symbol and for the effective amount of the delayed neutron fraction is used the β_{eff} symbol. The value of β_{eff} for a reactor varies with the average energy of neutrons that produce fission. To the reactor IPR-R1 TRIGA the β_{eff} is 0.0079. The chain reaction can be described quantitatively in terms of the multiplication factor k, which is defined as the ratio of the number of fissions in one generation divided by the number of fissions of the previous generation [16].

The basic purpose for the control system of nuclear reactors is to provide means to start the reactor, increase the power until a certain level, maintain this level and turn it off as part of routine operations. In normal working conditions, the core operates very close to criticality ($k \approx 1.0$). Small k deviations above or below 1, will result in insignificant changes in reactor power. In practice we use the term reactivity (ρ) to indicate how much the reactor is away from criticality ($k = 1$) or, the measure, in fraction of the multiplication factor, the withdrawal the system of the critical position. This is the most important operating parameter of a nuclear reactor. The expression that relates the reactivity (ρ) with the multiplication factor addition (K) is given by [17]:

$$\rho = \frac{\delta k}{1+\delta k} \qquad \rho = \frac{k-1}{k} \tag{1}$$

The normal operations of a reactor involve small changes of k (around 1), $k = 1.003$ means a $\delta k = 0.003$. The routine startup of the IPR-R1 TRIGA reactor is performed by the completely removing of the safety rods, which is available for fast shutdown of reactor. Then the control rods are raised in small steps and then it is doing the same with the adjustment rods. At each step (δk) , the movement of control rods is followed by neutronic increase. It is defined as the period (T) time in [s] to change this increase by a factor equal to the number "e" (2.718 ..). From the definition of the period is found the following expression for the neutronic variation, which is directly proportional to reactor power, ie [18]:

$$N(t) = N_0 \, e^{t/T} \tag{2}$$

Where:

N = neutron flux at any given time.
N_o = initial neutron flux.
T = period of the reactor (s)
t = time (s).
The relationship between the reactivity (ρ) and a stable period (T), with $k \approx 1$ is given by [19]:

$$\rho = \frac{\ell}{T(1+\delta \mathrm{k})} + \sum_{\mathrm{i=1}}^{6} \frac{\beta_{\mathrm{i}}}{1+\lambda_{\mathrm{i}} T} \tag{3}$$

Where:

ℓ = average lifetime of the neutron (neutron generation time) in (s) for the IPR-R1 TRIGA ≈ 100μs;
T = period of the reactor (s);
δk = increase in the multiplication factor;
β_i = fraction of delayed neutrons of group i;
λ_i = decay constant of delayed neutron group i (s-1).

The above equation is known as inhour equation. The term "inhour" comes from the expression of reactivity in units of inverse of the hours. The inhour is defined as a reactivity who corresponding to a stable period of 1 hour (T = 3600s) [16].

6.2 Thermal-hydraulic

The goal of the thermal and hydrodynamic design of the reactors is remove safely the heat generated without producing an excessive temperature in the fuel. Therefore, computer security codes are developed and employed, and are validated by experimental measurements. The study of the thermal behavior of nuclear reactors is divided into two areas: the temperature distribution within the fuel, and distribution in the coolant. Knowing the thermal parameters, the heat transfer equations are solved for the two areas [6]. The TRIGA-type reactors are characterized by their safety, mainly due to two factors related to heat transfer. They are:

- The large coefficient of the negative temperature / reactivity, ie, an increase in power leads to an increase in temperature of the moderator-fuel mixture, causing the appearance of a negative reactivity which gradually dampens the rate of increase in power stabilizing it.
- A passive system for removing heat from the core can operate at power up to 500 kW, in a steady-state, cooled only by natural circulation of pool water.

The regime of heat transfer in the fuel cladding is predominantly single phase in operations with power up to 100 kW with a temperature of about 180^{o}C in the fuel center. Operating in the new power of 250 kW, the heat transfer system on all core channels changes from the single phase natural convection regime to subcooled nucleate boiling and the temperature increases to about 300^{o}C in the center of the fuel, the positions of the central core. The forces of the coolant channels in the core are governed by the difference in densities of water at the bottom and top of the core. The higher the power, consequently the temperature difference between input and output in the channel, the greater the upward velocity of water [6].

The measure of nuclear reactors power is always done by means of nuclear detectors, which are calibrated by thermal means. The standard methodology for calibration of power developed by the IPR-R1 is based on energy balance in steady state, dissipated in the primary cooling circuit (Fig. 1) [12]. The thermal power generated by the core, as well as the fuel temperature, are the two main parameters considered as Operational Limits Conditions (OLC) [20].

6.3 Instrumentation

The IPR-R1 operational parameters are derived from their control instrumentation. Figure 2 shows the diagram of forced cooling system with the locations of the sensor measures of the neutronic parameters, cooling, and radiation protection, as shown below:

- Devices for indicating and moving the position of control rods.
- Fission chamber for the start-up channel (uranium-235) and associated instrumentation.
- Ionization chambers for monitoring the neutron flux (power) channels: Linear, Logarithmic and Percent, and monitoring of the "Period" and the "Reactivity" (velocity and criticality departure).
- Geiger Sensors for measure of the radiation level in various locations around the installation.
- Channels of temperature measurements with signals from five resistance thermometers (PT-100).

- Flowmeter for measure of cooling in the primary (orifice plate and differential pressure transmisssor).

As can be seen in the Fig. 2, the pool water is cooled by a heat exchange circuit, and a cooling tower. Thus the temperature of fuel at steady state depends on the environment temperature.

Some equipment was purchased and not yet installed. It is intended to install them in this project, they are:

- Thermocouples for monitoring the temperature of the core channels, the environment and in several points of the pool.
- Sensor and meter for monitoring the pH of the water of the primary circuit.
- Sensor and meter for monitoring the electrical conductivity of water pool.
- orifice plate and differential pressure transmitter to monitor the water flow at secondary.
- Instrumented fuel element for monitoring temperature and power of the core.

Information about the evolution of control systems and instrumentation used in nuclear reactors can be found in publications of the manufacturer of the TRIGA reactor (General Atomics) and international bodies of regulating the use of nuclear energy [21, [22], [23] [8] [9], [10], [11], [24] and [25].

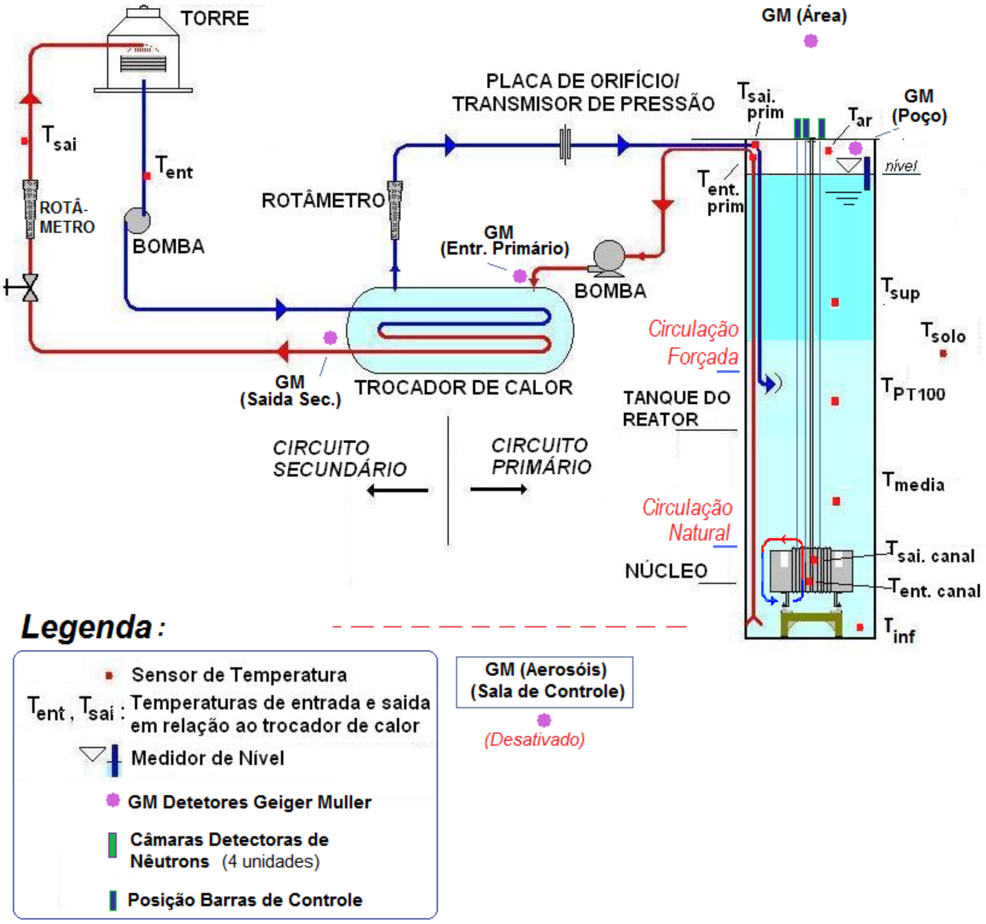

Figure 2: Forced cooling of the IPR-R1 TRIGA with the instrumentation used to monitor and control the operational parameters

6.4 Neutronic Parameters

All signs of the neutronic and radioprotection to be processed are from the analog outputs of the modules located in the instrumentation rack, with the exception of signs indicating the positions of control rods. The latter have their origins in the potentiometer located on each bars drive mechanism. The analog outputs of the rack modules are all 0 to 10 Vdc, except the sign of reactivity that is -10Vcc to + 10Vdc. The signal range of rods positions goes from 0 to 2.5 Vdc. The channel measurement modules will be placed in the test position. Variations will be made in the analog output signals, following the values in the control console indicators. Using a digital voltmeter the voltages will be recorded. With the data obtained will be found, through regression, equations for each parameter change electrical signals into engineering units. These equations will be included in the data acquisition program.

The method to be adopted for calculating the propagation of uncertainties will be based on the proposal of Kline and McClintock [24]. The following are the neutronic parameters and radiation protection [6]:

- Geiger counters for radioprotection located at: control room (aerosol), pool, resins, reactor area, primary and secondary circuit. The range is from 1 to 100 mR/h (logarithmic scale).
- Start-up Channel: indications ranging from 10^2 to 1.0×10^5 cps (logarithmic scale) from a fission chamber and associated electronics.
- Logarithmic Power Channel: indications in the range of 0.01 kW to 250 kW (logarithmic scale) from a compensated ion chamber.
- Linear Power Channel: indications ranging from 0 kW to 250 kW from a compensated ion chamber.
- Percent Power Channel: indications range from 2% to 120%, from an ionization chamber.
- Reactivity: indications range from -311 pcm to 1884 pcm, from the logarithmic channel.
- Period - (T): indications range from -0 (negative range) to ∞ (infinity) to 0 (positive range) on a logarithmic scale. The signal of the period comes from the module of the logarithmic channel.
- SUR - start-up power rate given in [dpm] (decades per minute), the inverse of the period (T), can be obtained using the equation: $SUR = 26.1 / T$ and T [s].
- Control rods: indications from 150 to 900 units, proportional to each rod position. In addition to the fitted equation that shows the position of the rod, will be also provide the equations that included the reactivity of each rod according to their position [27].

6.5 Thermal-Hydraulic Parameters

Following are listed the thermal hydraulic parameters and environmental conditions to be monitored. Some instruments do not exist in the circuit and will be installed in this project:

- Temperatures at pool and at inlet and outlet of the primary and secondary cooling system (5 resistance thermometers (PT-100).
- Primary and secondary water flow, measured by differential pressure transmitters.
- Fuel temperature, with signals provided by thermocouples located in the instrumented fuel element centre.
- Temperature of the core channels.
- Atmospheric pressure, relative humidity and temperature of the reactor environment.

- Conductivity and pH of water pool, corrected as a function of temperature.
- Power dissipated in the primary and secondary cooling system.
- Heat loss from the pool and in the primary circuit.
- Standard deviations of all variables mentioned above.

7. PROJECT PROGRESS

The research project presented here is continuation of the dissertation defended in the Pos-graduated Program at CDTN [26]. The work is highly experimental and is now being developed as a doctoral thesis in this same course. The developed system will cover the entire power range of the IPR-R1 reactor, ie, some mW to the maximum power of 250 kW. Among the innovations we can cite the inclusion of thermal hydraulics operational parameters, and the effect of core temperature on the neutronics variables.

The combination of DAQ (Data Acquisition) boards appropriate and the software LabVIEW® enables the build of virtual instruments (VI). The VI gives similar roles to traditional instruments, and is programmed via software with flexibility and advantages of manipulation, presentation and data records that are being measured or simulated. The user interface consists of two parts, which are the front panel and the block diagram. On the front panel can be created the control buttons, keys, LED indicators and graphical displays to present the data. The block diagram residing the blocks or icons that, properly interconnected, constitute the programming logic. For the development of the work were acquired data acquisition boards with interface USB (Universal Serial Bus), NI USB-6211 model and license to use the LabVIEW® software version 8.6, all manufactured by National Instruments [7]. At a later stage, the simulator will be adapted and receive signals from all the variables of the process performing the data acquisition and processing. Figure 3 shows a block diagram in development at the project.

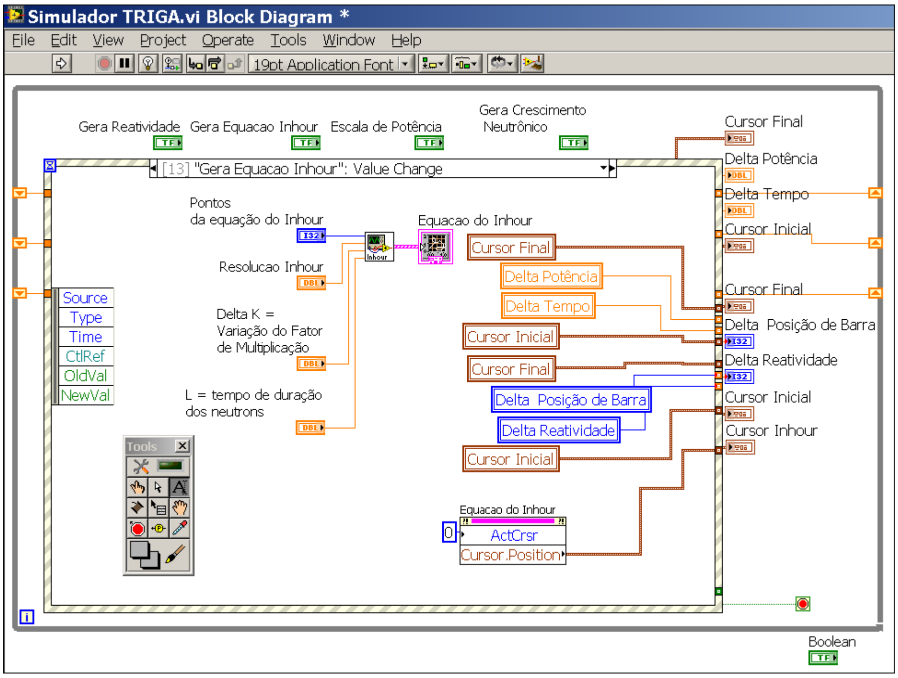

Figure 3. Block diagram of the system in development

The virtual console with drive control rods, their positions and a reactor core diagram is shown in the Fig. 4.

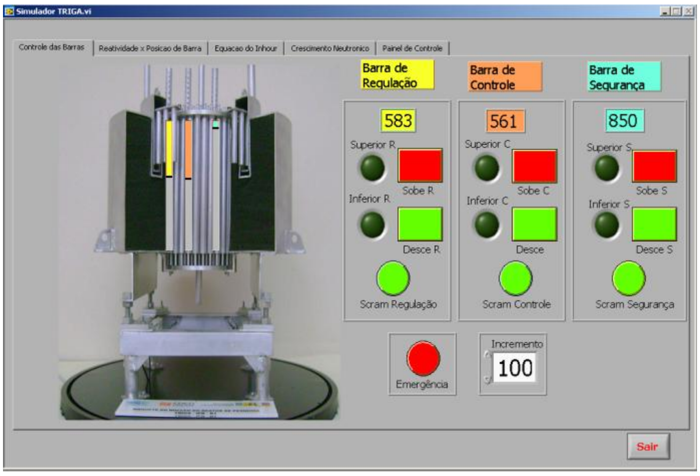

Figure 4. Main control panel

Fig. 5 shows two visual interfaces of the system on two video monitors. In the foreground there is the calibration curve of a control rod.

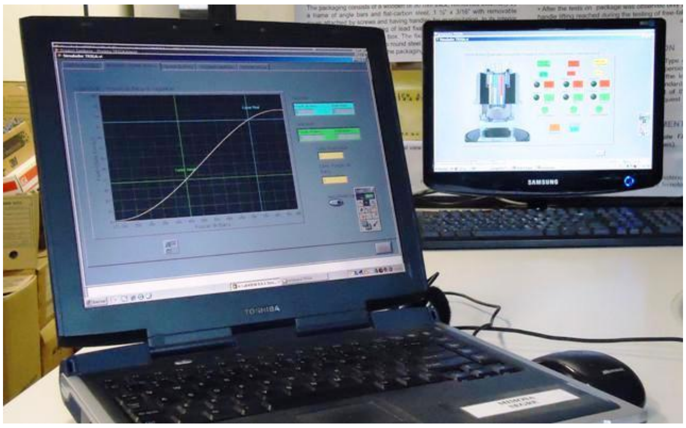

Figure 5. Visual interface on two video monitors

8. CONCLUSION

The resumption of nuclear power projects in Brazil can be noted in actions as the National Energy Plan 2030 that will complete the Angra 3 nuclear power plant, and includes the construction of at least four more units. The project of the Brazilian Multipurpose research Reactor (RBM) is also in progress. The current scenario indicates the need for training of personnel in reactor area and the Nuclear Technology Development Centre (CDTN) has a research reactor designed with the purpose of perform research and training in nuclear field.

The system described here for simulating the behavior of the operational variables of the IPR-R1 TRIGA reactor, will contribute to safety, quality and reliability in the operation of nuclear reactors. The system, with minor modifications, will be transformed into a supervisory system and will provide to this reactor a modern system to monitoring, in real time, the operating variables. Operational data will be stored and are available to staff and potential research could be conducted at the facility. The use of virtual instruments with visual interface on video monitors will enable the use of this reactor in personnel formation and training in the nuclear technology.

ACKNOWLEDGEMENTS

The authors express their thanks to: Nuclear Technology Development Centre (CDTN), National Nuclear Energy Commission (CNEN), Foundation for Research Support of Minas Gerais (FAPEMIG) and the National Council for Scientific and Technological Development (CNPq) for the partial financial support.

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