A human–machine interface for a TRIGA research reactor of Brazil

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Abstract: During seven years, the main operational parameters of the IPR-R1 TRIGA reactor of Nuclear Technology Development Centre (CDTN) at Belo Horizonte, Brazil, have been monitored and displayed online by using a data acquisition system developed for this reactor. Besides showing the real-time performance of the plant, the system stored the information in a computer hard disk, with an accessible historical database, in order to make the chronological information on reactor performance and its behaviour available to users. Some of the parameters stored are the control rod positions and reactivity, the reactor power, the fuel and water temperatures, the radiation levels, the primary cooling system flow, and the water pool level. Records of the reactor process variables are important for immediate or subsequent safety analyses to show the short and long-term trends, and to report the reactor operations to the organisation and external authorities. This paper describes the data acquisition system, and the electronic database developed for the IPR-R1 TRIGA reactor.

Keywords: TRIGA nuclear reactor; DAS; data acquisition system; HMI; human–machine interface.

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1 Introduction

The International Atomic Energy Agency recommends the use of safety and friendly interfaces for monitoring and controlling the operational parameters of nuclear reactors (IAEA, 1999a,b, 1998). One of the major applications of digital computing is on-line monitoring and display of reactor signals and information. Improvements in the awareness of a system status are an essential requirement to achieve safety in every kind of plant. In the case of nuclear reactors, progress is crucial to enhance the Human–Machine Interface (HMI) in order to optimise monitoring and analysing processes of reactor operational states. Operators and researchers of old-fashioned plants are concerned, and an upgrading of the whole console instrumentation is desirable in order to replace an analogue visualisation with a full-digital system (Memmi et al., 2016).

The 250 kW IPR-R1 TRIGA nuclear research reactor at Nuclear Technology Development Centre (CDTN), a research institute of the Brazilian Nuclear Energy Commission (CNEN), has been operated for 64 years. The main operational parameters are monitored by analogue recorders and counters located in the reactor control console. The reactor operators register the most important operational parameters and data manually in the reactor logbook. This process is quite useful, but it can involve some human errors, parallax error, time delay, etc. It is also difficult for the operators to take notes of all variables involving the process mainly during fast power transients in some operations (IAEA, 2008, 2002).

Owing to the experiments on neutronics, thermohydraulics and reactor power calibrations, the development of a Data Acquisition System (DAS) was necessary to make possible the experiences performance (Souza and Mesquita, 2011; Mesquita et al., 2014). New temperature and flow sensors were also included in the circuit (Mesquita et al., 2011a, b). Now, this DAS is part of the IPR-R1 reactor operational procedures, and it is used to monitor the operational parameters and to maintain the electronic files. The data acquisition based on digital computer system (microprocessor) designed for the reactor, allows online monitoring, through graphic interfaces, and shows operational parameters' evolution for operators. Some parameters that were not measured, like the power and the coolant flow rate at the primary loop, are monitored now in the computer video monitor. The developed system allows measuring the parameters at frequencies up to 1 kHz. These data are also recorded in text files available for query and analysis. The video monitor provides real time information, shows all reactor operations graphics and displays the operating parameters, and the DAS saves all the operational information in the hard disk (Mesquita et al., 2011c). The system conforms to the recommendations of the IAEA, and of other international organisations on monitoring and recording of the operational variables (NRC, 2006; IAEA, 1999a,b; 2002; IEEE, 2003).

CDTN intends to adopt its laboratories to ISO's (International Organization of Standardization) standards to show reliability in its results (ISO, 2016). The international standardisation began for the electrotechnical field with the formation in 1906 of the International Electrotechnical Commission (IEC, 2016). This commission, of which Brazil is a member, is an international organisation of electric, electronics and related technologies standardisation, and some of its norms are developed together with ISO. According to ISO 9000 standard, an institution must follow some steps and take care of certain requirements to be certified. For example, to calibrate the processes parameter to assure the quality of the product or service, to implement and to keep adequate registers to ensure the traceability of the process and to undertake a systematic review of procedures and quality system to ensure its effectiveness.

CDTN offers the Training Course for Research Reactor Operator (CTORP). This course is offered since 1974 and about 250 workers were certificated by CDTN. The CTORP is a three-week practical training course using the IPR-R1 TRIGA. During the last decade, there was a recovery of several areas of research in CDTN research institute, leading to the creation of the Graduate Program in Science and Technology of Radiation, Minerals and Materials. With the conclusion of Angra 3, the design and construction of the Brazilian Multipurpose Reactor (RMB) and the resumption of the Brazilian nuclear program, it is anticipated there will be a large demand for training in nuclear technology. CDTN is now an academic environment and it is an ideal place for reactor operation education. In order to perform a research program and training using the IPR-R1 reactor it is necessary the update of its instrumentation for monitoring of operational parameters. The new system would be microprocessor based, and would utilise large LCD displays that are typical of state-of-the-art control rooms. Therefore, the graduates would find the same type of control system of a typical reactor control room (Mesquita et al., 2011d).

The digital system is being developed to monitor, store and simulate the behaviour of operating parameters. User-friendly interface computer video screens are used to show the reactor system parameters. The graphical interfaces provide greater reliability and transparency in IPR-R1 TRIGA reactor operations. Besides allowing online reactor parameters visualisation and transmission through the internet or in the networks, the data can be stored and made available for exercises (Mesquita et al., 2011c).

2 Materials and methods

These signals are acquired from normal instrumentation of the plant and displayed on monitors in the control room and other key locations. This provides the reactor operator and users with the necessary information about the reactor status. Signals acquired by the computer may include those related with reactor safety and operation from both nuclear and process channels. Figure 1 shows two photographs of the pool and the core with the IPR-R1 TRIGA reactor in operation.

The reactor instrumentation includes four neutron channels that are fed by three neutron-sensitive ion chambers (two compensated and one uncompensated), and by one fission chamber located around the core. The other analogue signs, collected by the data acquisition system, are outputs of the reactor control console and from some digital indicators or directly from the thermocouples.

Figure 1 The 250 kW IPR-R1 TRIGA reactor pool and core

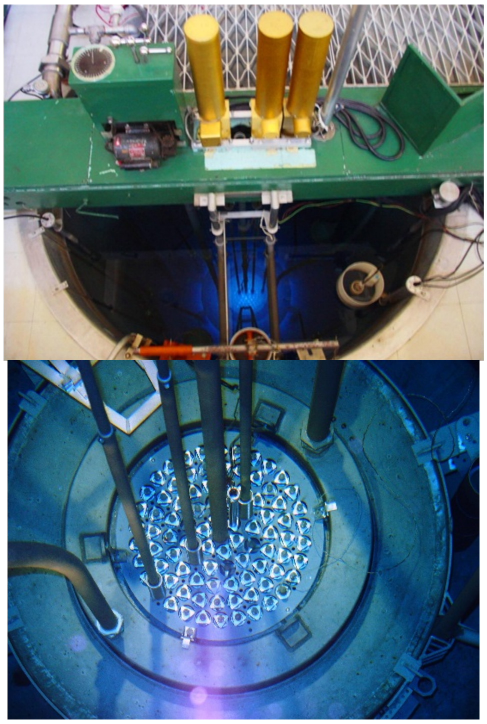
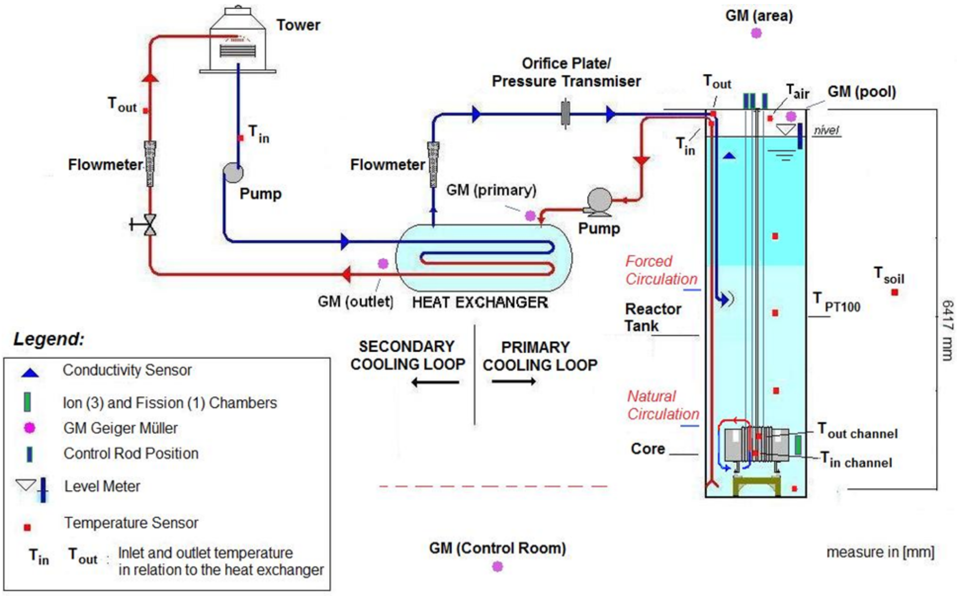


Figure 2 shows the reactor cooling system diagram and the location of the instrumentation used to monitor the operational parameter. The detector´s signals are amplified in a voltage amplifier. The amplified output voltage is between 0 to ± 10V which is the input sign of the Multiplexing Board and to the Analogue to Digital Converter card of the PC with the associated software (Figure 3). The measure data are shown in the LCD computer video monitor. Owing to the high impedance of the cards input, they do not cause any disturbance in the indications at the reactor control console. The main components of the instrumentation are described in the next sections.

Figure 2 IPR-R1 TRIGA reactor cooling system and instrumentation distribution



2.1 Amplifier and multiplexing board

The analogue signs are received in three model PCLD-789 cards by Advantech Co (Advantech, 2003) connected in cascade, each one with 16 channels, which total 48 inputs. These cards prepare the signs amplifying and filtering the noises, and make the connection for a unique analogue output (multiplex action). One of the cards receives the signs directly from the thermocouples (range of ± 100 mV). It has a sensor that measures the temperature and makes the compensation of the cold junction adjusting the measured value. The other cards receive the signs from the control console (range of ±10 V). The main characteristics of the conditioning cards are:

- Accuracy: 0.0244% of the range ±1 LSB;
- Input: 16 differential channels;
- Over voltage protection: ±30 V continuous;
- Input range: ±10 V maximum, varies with gain selection;
- Gain: 1, 2, 10, 50, 100, 200, 500 and 1000;
- Cold junction compensation: +24.4 mV/°C (0.0 V at 0.0 °C).

Tables 1, 2 and 3 show the identifications of each signal collected by the cards. In the first column, it is presented the number of the entrance channel in each card. In the second column it is presented the identification (code) that is used in the data acquisition program to equation the collected sign, where: AI = analogue input and TMP = thermocouple. Finally, the third column shows the description and range which the collected sign were obtained.

Figure 3 Data acquisition connection cards

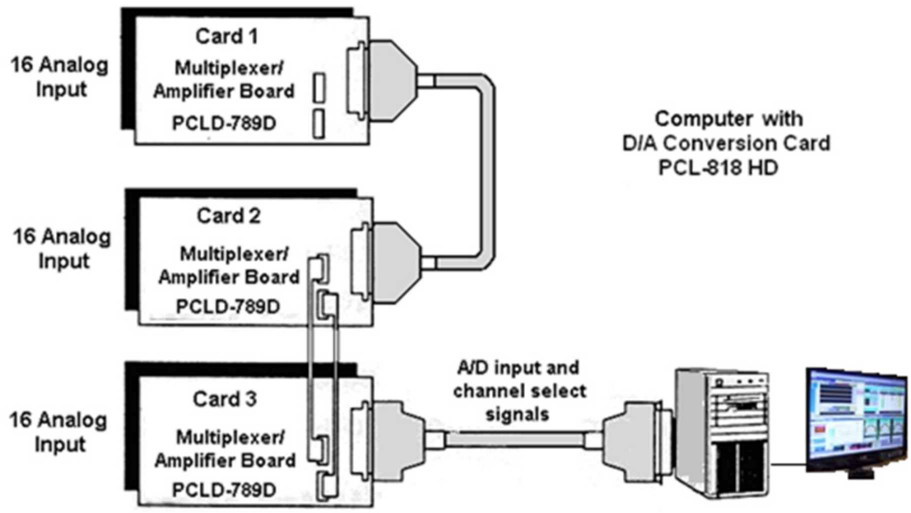


Table 1 Signals distribution in the card 1, gain = 50

Channel	*Analogical input*	*Collected sign*
0	TMP 1	Core Channel Temperature (upper), (thermocouples, –6 to 55 mV)
1	TMP 1	Fuel Temperature (upper), (thermocouples, –6 to 55 mV)
2	TMP 2	Fuel Temperature (medium), (thermocouples, –6 to 55 mV)
3	TMP 3	Fuel Temperature (lower), (thermocouples, –6 to 55 mV)
4	TMP 4	Air Temperature above the Pool, (thermocouples, –6 to 55 mV)
5	TMP 5	Pool Water Temperature (upper), (thermocouples, –6 to 55 mV)
6	TMP 6	Pool Water Temperature (medium), (thermocouples, –6 to 55 mV)
7	TMP 7	Pool Water Temperature (lower), (thermocouples, –6 to 55 mV)
8	TMP 8	Soil Temperature 1, (thermocouples, –6 to 55 mV)
9	TMP 9	Core Channel Temperature (lower) (thermocouples, –6 to 55 mV)
10	AI 21	Pool Water Temperature (PT-100, 4 to 20 MA)
11	AI 4	Secondary Circuit Inlet Temperature, (PT-100, 4 to 20 mA)
12	AI 5	Secondary Circuit Outlet Temperature, (PT-100, 4 to 20 mA)
13	AI 1	Primary Circuit Water Flow, (4 to 20mA)
14	AI 2	Primary Circuit Inlet Temperature, PT-100, (4 to 20 mA)
15	AI 3	Primary Circuit Outlet Temperature, PT-100, (4 to 20 mA)

Table 2 Signs distribution in the card 2, gain = 1

Channel	*Analogical input*	*Collected sign*
0		Reserved to be used for air relative humidity
1	AI 6	Logarithmic Channel Power, (0 to 10 V)
2	AI 7	Lineal Channel Power, (0 to 10 V)
3	AI 8	Percent Power Channel, (0 to 10 V)
4	AI 14	Neutron Flux Period, (0 to 10 V)
5	AI 15	Reactor Core Reactivity, (–10V to +10 V)
6	AI 16	Start-up Channel Counting, (0 to 10 V)
7	AI 18	Safety Control Rod Position, (0 to 2.5 V)
8	AI 19	Shim Control Rod Position, (0 to 2.5 V)
9	AI 20	Regulation Control Rod Position, (0 to 2.5 V)
10	–	Aerosols Radiation (disabled), (0 to 10 V)
11	AI 9	Pool Radiation, (0 to 10 V)
12	AI 10	Area Radiation, (0 to 10 V)
13	AI 11	Primary Circuit Inlet Radiation, (0 to 10 V)
14	AI 12	Ion Changer Radiation, (0 to 10 V)
15	AI 13	Secondary Circuit Inlet Radiation, (0 to 10 V)

Table 3 Signs distribution in the card 3, gain = 50

Channel	*Analogical input*	*Collected sign*
0	–	–
1	TMP 11	Pool Temperature, upper 2, thermocouples, (–6 to 55 mV)
2	TMP 12	Pool Temperature, upper 3, (thermocouples, (–6 to 55 mV)
3	TMP 13	Pool Temperature, upper 4, (thermocouples, (–6 to 55 mV)
4	TMP 14	Pool Temperature, upper 5, (thermocouples, (–6 to 55 mV)
5	TMP 15	Pool Temperature, upper 6, (thermocouples, (–6 to 55 mV)
6	TMP 16	Pool Temperature, upper 7, (thermocouples, (–6 to 55 mV)
7	TMP 17	Soil Temperature 2, (thermocouples, (–6 to 55 mV)
8	TMP 18	Thermocouple spare, (thermocouples, (–6 to 55 mV)
9 a 15	–	Spares (water pH, conductivity, etc.)

2.2 Analogue/digital conversion card

The outputs of the three conditioning cards are addressed to the analogue input plug of the data acquisition card, model PCL-818hd by Advantech Co. (2003). This is a high-speed data transference card installed in the computer case, which transforms the analogue input signs into digital signs. This card has the following main characteristics:

- Accuracy: 0.01% of the range ± 1 LSB;
- Resolution: 12 bits;
- Sampling rate: up to100 kHz with DMA transfer;
- Over voltage: continuous ±30 V max.

2.3 Data acquisition software

We used the program VisiDAQ a Windows-based data acquisition. In addition to typical human–machine interface (HMI) functions, VisiDAQ features a Visual Basic programming environment, and it provides numerous graphical control and display icons. Users can arrange control and display icons by dragging and dropping them on screen, resulting in a dynamic, real-time display of process data (Advantech, 2016). The data acquisition system was programmed with a set of icons that represents controls and functions, available in the menu of the software. Such a programming is called visual programming. The user interface consists of two parts: a front panel and a diagram. The front panel is used for input and output controls, and to display the data whereas the circuit resides on the circuit board. The front panel has buttons, indicators and graphics and display functions. This interface also calculates mean and standard deviation of the data and plots it.

3 Results and discussion

The main indications of the control console are collected by the data acquisition system, including the positions of the three control rods. These signs come from the rack of the instruments and from the reactor control console and they input in channels 1 to 15 of the Card 2. A description of all signs collected from the control console is not included in this paper. It was accomplished all the answers of the parameters collected, and the equations used to transform the voltage signals into engineering units were introduced in the data acquisition program.

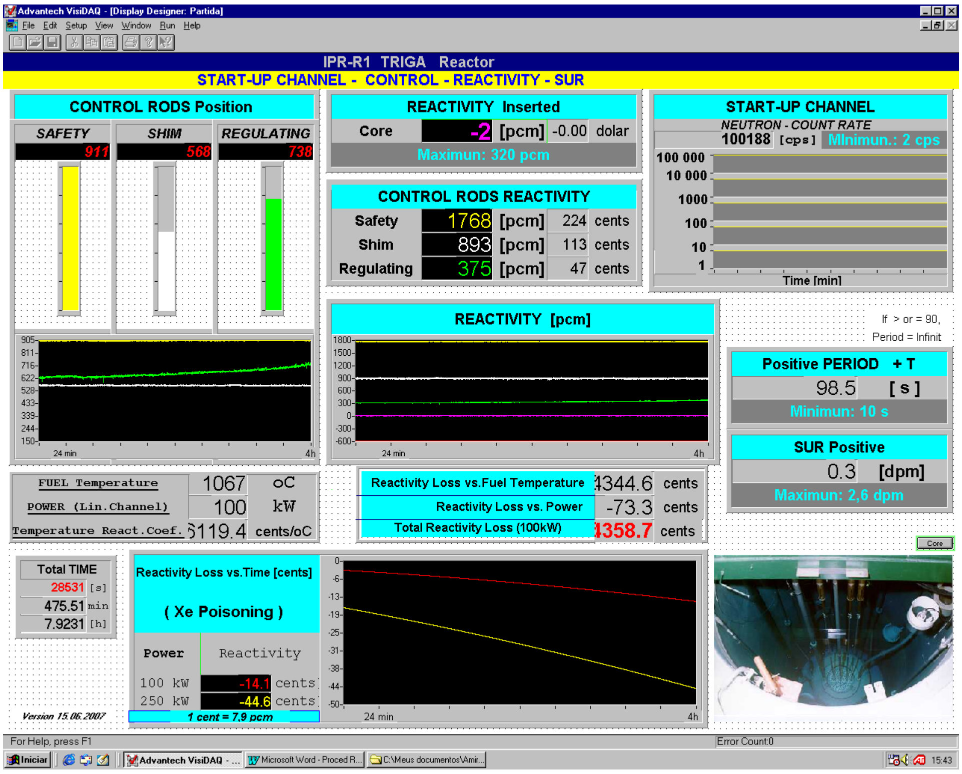
Some theoretical evaluations were performed using thermal hydraulics codes, and neutronic code. The calculations results agree with the evolution of the parameters shown by the data acquisition system. These simulations can be found among other works in Mesquita et al. (2016, 2014, 2012) and Reis et al. (2012).

Several screens can be developed easily depending on the need of operation. The main display is a navigation screen, where it is possible to access any of the four graphic interfaces divisions of the program by using the mouse. From this screen, it is also possible to start the data-recording key. Thus, it is possible to know the evolution of the reactor's parameters in each one of the interfaces in real time.

3.1 Control, start up channel, period and reactivity

On the screen, shown in Figure 4, the start-up of the reactor can be accompanied through the neutron evolution-counting rate. The positions of the three control rods of the reactor can be visualised in graphics and in digital indicators. The evolution of the control rods position and its reactivity, in the last 60 minutes, are shown in three graphics. The reactor reactivity in [pcm] and in [dollar], is given by digital counters. This screen also shows the loss of reactivity as a function of power and time, the positive period of the reactor (T) in [s] and the start-up rate (SUR) in [dpm].

Figure 4 Control, startup channel, period and reactivity screen



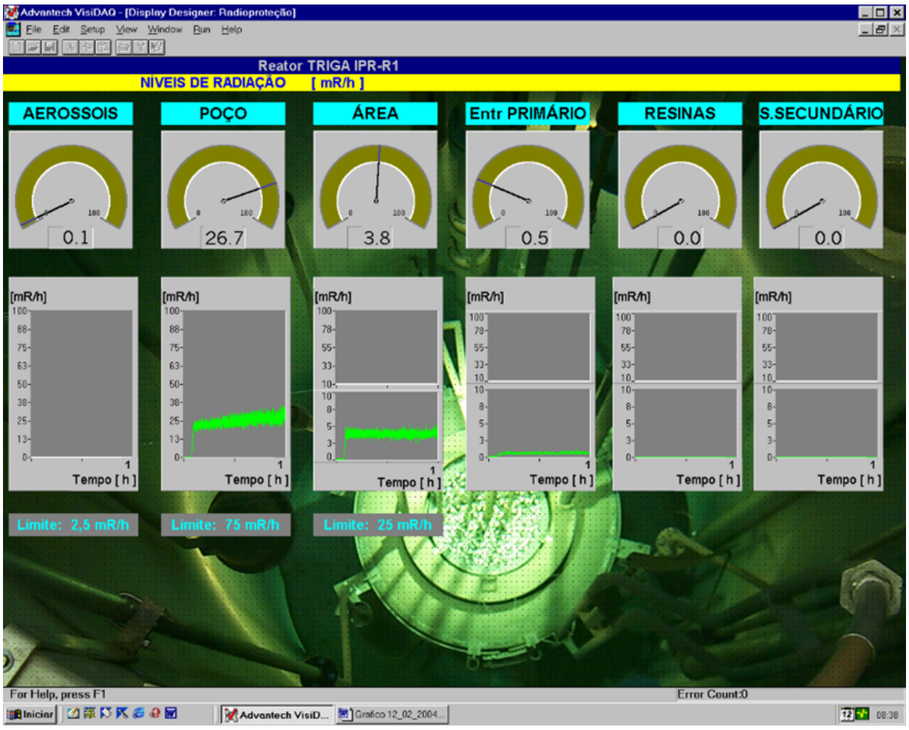
3.2 Radiation levels

The gamma radiation levels at the reactor are measured in the following positions (see Figure 2):

- in the Control Room (AEROSSOIS);
- at about 30 cm above the reactor pool (POÇO);
- at 2 m above the reactor pool (AREA);
- at the inlet piping of the primary cooling loop heat exchanger (ENTRADA PRIMÁRIO);
- in the ion exchanger system (RESINAS);
- at the outlet piping of the secondary cooling loop heat exchanger (SAÍDA SECUNDÁRIO).

These radiation levels of the monitoring channels are shown on the screen in analogue and digital indicators (Figure 5). Their evolution in the last 60 minutes is presented in graphic ways also.

Figure 5 Radiation monitoring system



3.3 *Cooling system and temperatures*

All the following parameters of the primary and secondary cooling loops are shown on the screen (Figure 6):

- the average values of the inlet and outlet temperatures of the primary and secondary loops, the flow rate, the reactor pool temperatures, and all standard deviations;
- the power dissipated in the primary and secondary cooling loops; the air temperatures above the reactor pool and in two points of the soil;
- the average temperature taken from three thermocouples of the instrumented fuel element;
- the time elapsed since the program has begun, in [s], [min] and [h].

3.4 *Power channels*

Figures 7 and 8 show the video-screen displays that consolidate information for the reactor power status in real time. Both screens show the power supplied by the three conventional neutron measures channels: Logarithmic Channel, Linear Channel and Percent Power Channel, and by the news power channels developed by Mesquita et al. (2011a). These latter channels use thermal means, i.e., fuel temperature and energy balance.

Figure 6 Cooling system and temperatures screen

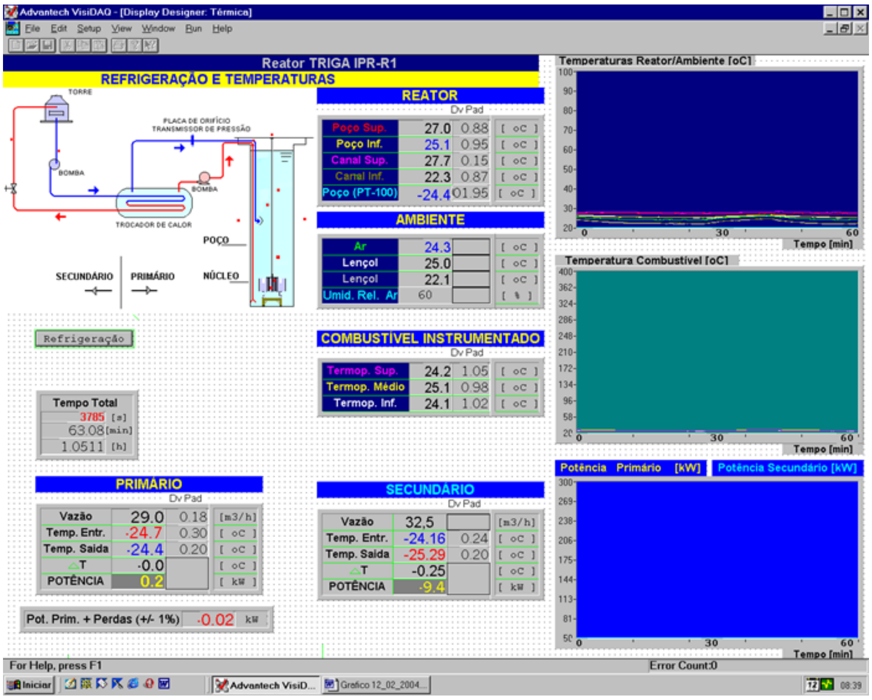


Figure 7 Power level channels screen

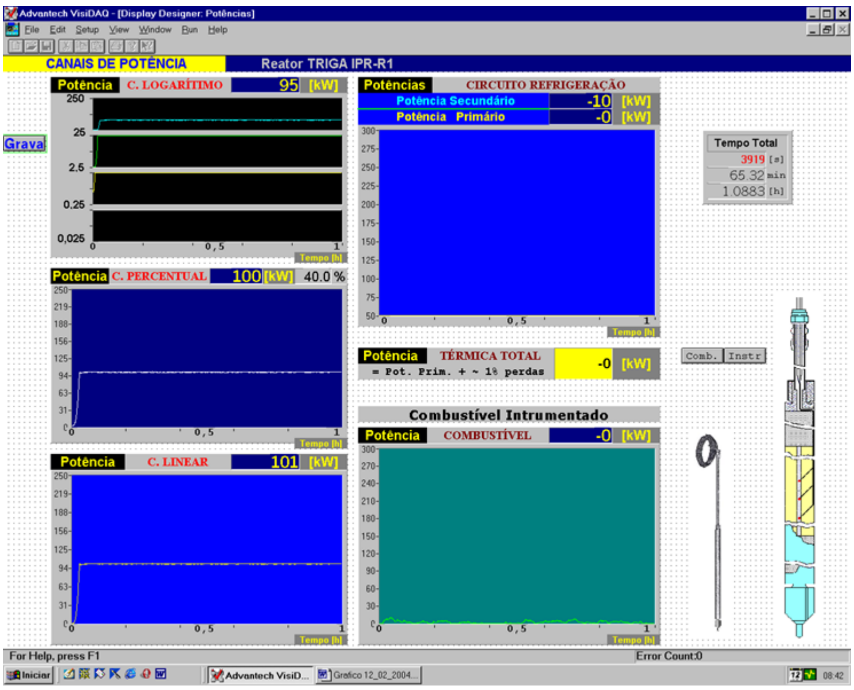
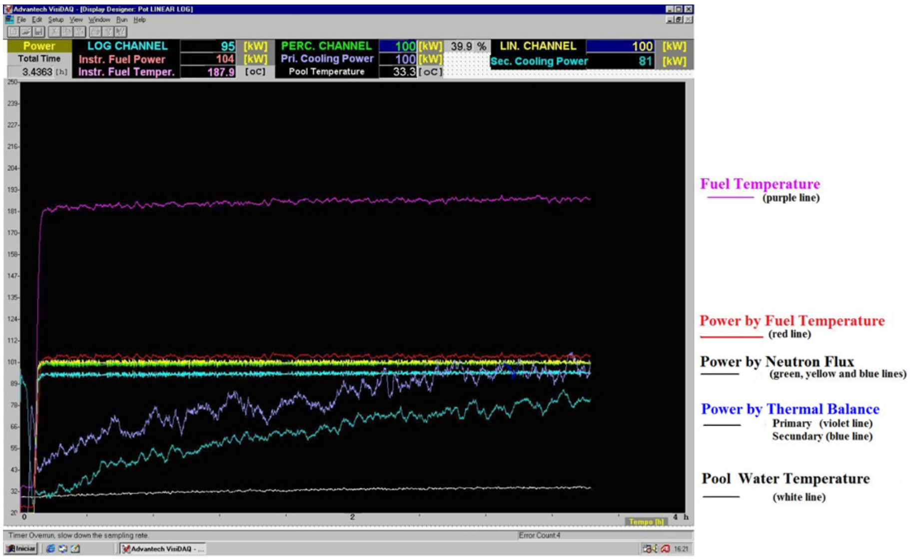


Figure 8 Power monitoring screen on the same chart



Digital indication and graphics show the last 60 minutes values. The evolution of the power dissipated in the primary and secondary cooling systems is also shown. After several hours of reactor operation, when it reaches thermal balance with the environment, the power of the reactor will be closer to the power dissipated in the primary coolant loop, and the thermal losses will be smaller. Those losses values are indicated on the screen. The reactor power is monitored also by the increase of the temperature in the centre of an instrumented fuel by thermocouples.

3.5 Database system

The database is a computerised collection of the operational parameters, organised so that it can be expanded, manipulated, and retrieved rapidly for various uses. Within the electronic database, a computer program assists the user in selecting desired pieces of data. The data are recorded in five separated text-files that permit to register 40 parameters. In all files, the first column is always the time registration in [s]. The data collection and recording frequency can be adjusted starting from 1.0 Hz to 1.0 kHz. The frequency usually used is equal to 1 Hz.

Figures 9 and 10 show the IPR-R1 database with all operation files from the year of 2002 until 2009. The data is recorded in text files (.txt) (Figure 9) and after it is passed to Excel software to allow the visualisation of variables evolution (Figure 10). Safety backup is made to other computers and available in the Ethernet.

The trend of a series of data can be analysed from the curve charts. An example of display pattern of results data is shown in Figure 11.

Figure 9 IPR-R1 TRIGA operation database in Microsoft text files

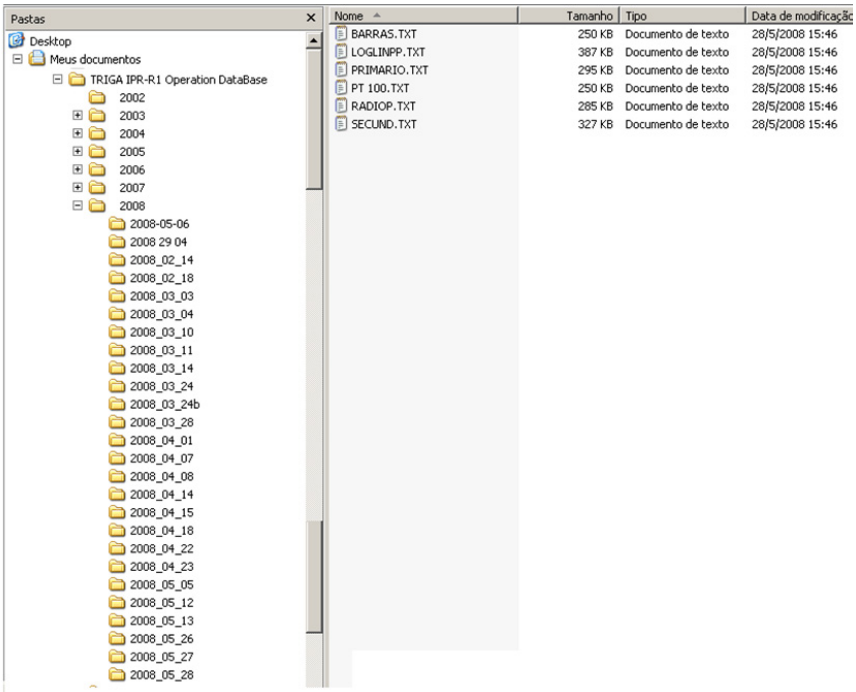


Figure 10 IPR-R1 TRIGA operation database in Microsoft excel files

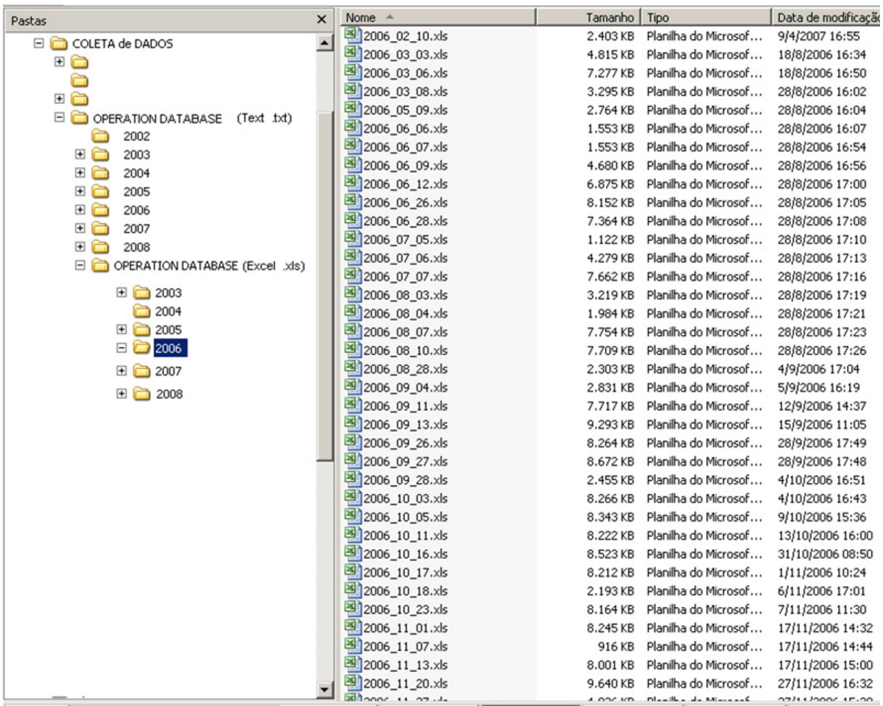
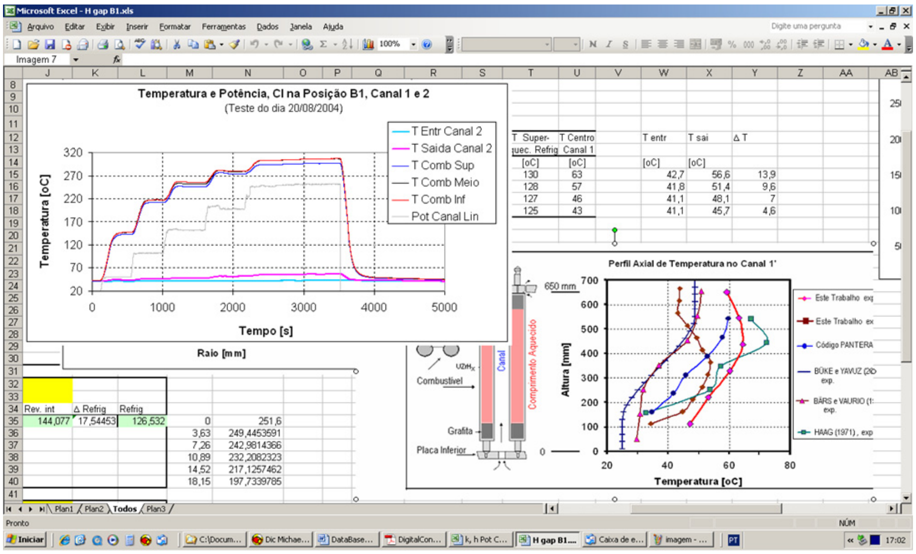


Figure 11 Example of the data display pattern of results data



4 Conclusions

Nuclear reactor operators need to know the basic behaviour of reactors in order to understand and safely operate them. Nuclear reactor instrumentation is designed to emphasise the reliability, redundancy and diversity of control systems (Blake, 2006; Holcomb and Wood, 2006). A new data acquisition based on the microcomputer has been designed and developed to allow the real-time collection of all IPR-R1 TRIGA reactor operational parameters and information from the reactor console. In every operation of the research reactor, about forty variables are registered by the data acquisition system. They are fed into the computer through an interface unit that includes hardware like multiplexer, A/D converter and computer interface. Information on all aspects of reactor operation is displayed on the computer screen. The colour graphic monitors can display real-time operation data in concise, accurate, and easily understood formats. Bar graph indicators and visual and audible enunciators are provided. Information displayed on the monitor is recorded on hard disk copy. The system collects data during reactor operations and stores it in a historical database. This record is a powerful tool that can be used for operations review and maintenance troubleshooting (IAEA, 2000). Compared with the existing analogue system, the digital system has a wider dynamic range, less noise in low power range, and a comparable system response time.

The choice of a research reactor for testing the developed system relies on its training and didactic importance for the education of plant operators: in this context, a digital instrument can offer a better user-friendly tool for learning and training. It is worthwhile to remark that such a system does not interfere with the console instrumentation, the latter continuing to preserve the total control.

The IPR-R1 TRIGA nuclear reactor is used for education, particularly for the needs of the Brazilian Nuclear Power Plants operators' training. Thus, a digital system was developed to monitoring the behaviour of the main variables related to the routine start-up of the reactor in order to assist in the training conducted with this reactor. Students of physics and post-graduate students of nuclear engineering can carry out practical exercises using the data acquisition system.

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