Digital Systems Implemented at the IPEN Nuclear Research Reactor (IEA-R1): Results and Necessities

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***Abstract*—IPEN (Nuclear and Energy Research Institute) was founded in 1956 with the main purpose of doing research and development in the field of nuclear energy and its applications. It is located at the campus of University of Sao Paulo (USP), in the city of Sao Paulo, in an area of nearly 500,000 m2. It has over 1.000 employees and 40% of them have qualification at master or doctor level The institute is recognized as a national leader institution in research and development (R&D) in the areas of radiopharmaceuticals, industrial applications of radiation, basic nuclear research, nuclear reactor operation and nuclear applications, materials science and technology, laser technology and applications.**

Along with the R&D, it has a strong educational activity, having a graduate program in Nuclear Technology, in association with the University of Sao Paulo, ranked as the best university in the country. The Federal Government Evaluation institution CAPES, granted to this course grade 6, considering it a program of Excellence. This program started at 1976 and has awarded 458 Ph.D. degrees and 937 master degrees since them. The actual graduate enrollment is around 400 students.

One of major nuclear installation at IPEN is the IEA-R1 research reactor; it is the only Brazilian research reactor with substantial power level suitable for its utilization in researches concerning physics, chemistry, biology and engineering as well as for producing some useful radioisotopes for medical and other applications.

IEA-R1 reactor is a swimming pool type reactor moderated and cooled by light water and uses graphite and beryllium as reflectors. The first criticality was achieved on September 16, 1957. The reactor is currently operating at 4.5 MW power level with an operational schedule of continuous 64 hours a week.

In 1996 a Modernization Program was started to establish recommendations in order to mitigate equipment and structures ageing effects in the reactor components, detect and evaluate obsolescence of some electrical and electronic systems. In this work we will show a retrospective and results of digital systems applied to IEA-R1 reactor concerning electronic equipments and systems refurbishment and modernization and the necessity of a new control console implementation.

***Key words* - Data Acquisition, Nuclear Instrumentation, Nuclear Research Reactors**

I. INTRODUCTION

The IEA-R1 reactor is a multidisciplinary facility used extensively for basic and applied research in nuclear and neutron related sciences and engineering. The reactor produces some radioisotopes with applications in industry and nuclear medicine, performs miscellaneous irradiation services, and has been used for training as well. Several departments of IPEN routinely use the reactor for their research and development work. Many scientists and students at universities and other research institutions in Brazil also use it quite often for academic and technological research. However, the main user of the reactor is the staff of the IEA-R1 Research Reactor Center (CRPq) with interest in basic and applied research in the areas of nuclear and neutron physics, nuclear metrology, and nuclear analytical techniques.

This facility is a swimming pool type reactor, light water moderated and with graphite reflectors, designed and built by Babcock & Wilcox Co. Start up operation and first criticality was obtained in September 16th, 1957.

Although designed to operate at 5 MW thermal power, in the first three years the maximum power operation was 1 MWth and later 2 MWth in order to attend radioisotope production. The reactor is currently operating at 4.5 MW on a 64h per week cycle.

Until 1980, all ^{99}mTc generators used in the country were imported. To meet the ever increasing demand for this important radionuclide, IPEN started producing its own ^{99}mTc generator kits from fission ^{99}Mo purchased from Canada.

In order to reduce the heavy importation costs of the primary radioisotope ^{99}Mo, as well as to minimize increasing reliance on only few world suppliers of this product, IPEN concluded a decision making process, starting the production of ^{99}Mo inside its own nuclear reactor using (n,γ) reaction.

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Aiming at the local production of ^{99}Mo, precursor of the radioisotope ^{99}mTc and widely used in nuclear medicine, the institute invested considerable effort, during the 1996-2005 period, to upgrade the reactor power from 2MW to 5MW and operational cycle from 8h a day/5 days a week to 120h continuous per week [1].

For this purpose, several modifications in the reactor systems and components had to be implemented. At the same time, a vigorous ageing management, inspection and modernization program was developed [2]. Fig. 1 shows the reactor pool and its core structures.

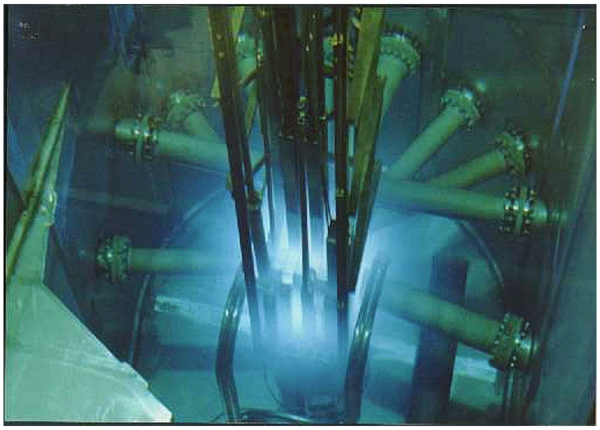

Fig.1. IEA-R1 reactor at work

II. NUCLEAR RESEARCH REACTORS IN BRAZIL

Research reactor utilization has more than fifty years in Brazil. Brazil has four nuclear research reactors (NRR), the first three reactors, constructed in the late 50´s and early 60´s at university campus in Sao Paulo, Belo Horizonte and Rio de Janeiro, and had their utilization for training, teaching and nuclear research. The IPEN/MB-01 reactor, designed and constructed at IPEN in the late 80´s, is utilized for the development and qualification of reactor physics calculations for PWR core application and as a critical unit (zero power reactor).

Beside the NRR Brazil has two nuclear power plants currently in operation, one unit starting construction and four more units planned for the next two decades. Some details of the characteristics of brazilian research reactors are summarized in Table 1.

TABLE 1 BRAZILIAN RESEARCH REACTORS

	IEAR1	IPER1	ARGO	IPEN_MB
Criticality	1957	1960	1965	1988
Operator	IPEN	CDTN	IEN	IPEN
Location	SP_Br	MG_Br	RJ_Br	SP_Br
Type	POOL	TRIGA	ARGO	Z.Power
Th.Power	2-5MW	250KW	200W	100W
Enrichm	20%	20%	20%	4.3%
Supplier	B&W	G.A.	USDOE	Brazil

III. IEA-R1 NUCLEAR RESEARCH REACTOR

IEA-R1 reactor was the first nuclear reactor in the south hemisphere, as a result of the U.S. program "Atoms for Peace". The operation of the reactor started on 1957, when it reached criticality for the first time. Since 1957 until 1973 there was an "electronic division" responsible for two main tasks: to develop small projects, in order to attend the necessities of the researchers, and to provide maintenance for all the instruments in the Institute, mainly the ones related to the reactor. In 1973 the Direction of the Institute noticed that the technical staff had the capability to develop some instruments and started a nationalization program. However, by that time importation was easy, and since the economy of Brazil was growing, it was difficult to maintain the same professionals working together for long periods. For these reasons the nationalization program was too slow, and when the prototypes were finished, they were already obsolete. Another event that contributed to slow down the nationalization program was the renewing of the reactor instrumentation. The original instrumentation was suplied by Babcock & Wilcox, and installed in 1957, when the reactor went critical for the first time

In 1974 a new instrumentation system was bought from General Atomic, a U.S. company. It was composed by a new set of rod drive mechanisms, process and area radiation monitors, safety channels, scram circuitry, instrumentation panels and a new operator's console. The new system was installed in 1976, and excluding the radiation and neutron detectors, all other field instruments were maintained as originally installed [3].

Although the basic structures are almost the same as the original project, several improvements and changes in components, systems and structures had been made along the reactor life (since 1974).

During 55 years, the reactor was used mainly in basic and applied research, neutron activation analysis, and produced radioisotopes for medicine, industry, universities and research centers.

In 1995, considering a favorable budget from the Federal Government, and the priorities given to the production of radioisotopes, the project to upgrade the IEA-R1 operation thermal power was implemented.

To achieve the upgrading (5 MW) and 5-day continuous operation goals to allow the commercial radioisotope production, the project was divided in three main groups of actions: a) Improvement of fuel element production; b) Adequacy of systems, structures and components, and c) Adequacy of radioisotope production [4].

IV. IMPORTANT IMPROVEMENTS MADE IN THE REACTOR (DIGITAL SYSTEM)

To accomplish safety requirements demanded by the Brazilian Regulatory Body (Nuclear Energy National Commission-CNEN) to upgrade reactor power level, a set of actions were made which involved the adequacy of old components (ageing program) and design of new ones, featuring engineering systems, risk analysis, safety evaluation and licensing [2]. In this case the improvement in some monitoring system (pumps, data acquisition and a technological proposal in the design of a new control console) will be shown.

A. Cooling System Pumps Monitoring (Primary and Secondary Loops)

The IEA-R1 reactor also had components changed due to ageing, and are monitored in operation by a Pumps Vibration Monitoring System.

The objectives of this system were to establish a strategy to monitor and diagnose vibrations of the motor pumps used in the primary reactor cooling system of the IEAR1 nuclear research reactor, to verify the possibility of using the existing installed monitoring vibration system and to implement such strategy in a continuous way. Four types of mechanical problems were considered: unbalancing, misalignment, gaps and faults in bearings. An adequate set of analysis tools, well established by the industry, was selected. These are: global measurements of vibration, velocity spectrum and acceleration envelope spectrum. Three sources of data and information were used; the data measured from the primary pumps, experimental results obtained with a Spectra Quest machine used to simulate mechanical defects and data from the literature. The results shown that, for the specific case of the motor-pumps of IEAR1 nuclear research reactor, although the technique using the envelope of acceleration, which is not available in the current system used to monitor the vibration of the motor-pumps, is the one with best performance, the other techniques available in the system are sufficient to monitor the four types of mechanical problems mentioned [5].

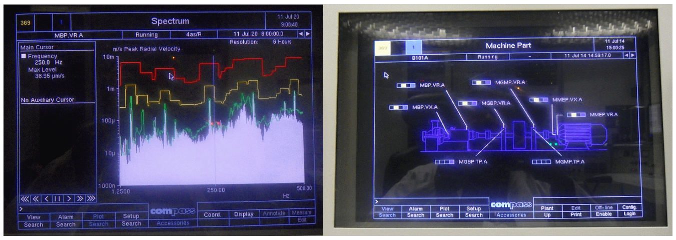

Fig. 2. Cooling system pumps monitoring (control room)

B. Data Bank System

Due to the need of several other centers to access some information about reactor nuclear, thermohydraulic and radiation protection parameters, a Data Bank for IPEN scientific community was designed and implemented.

The objective of this work was to present the relational database, named FALCAO. It was created and implemented to support the storage of the monitored variables in the IEA-R1 nuclear research reactor, located in the Instituto de Pesquisas Energéticas e Nucleares, IPEN - CNEN/SP. In this database all IEA-R1 operational dada are stored: nuclear, thermohydraulic and radiation protection parameters, as well as digital data from a domestic meteorologic tower (2010) are able to scientific staff.

The data logical model and its direct influence in the integrity of the provided information were carefully considered. The concepts and steps of normalization and de-normalization including the entities and relations involved in the logical model are presented. It is also presented the effects of the model rules in the acquisition, loading and availability of the final information, under the performance concept since the acquisition process loads and provides lots of information in small intervals of time. The SACD application, through its functionalities, presents the information stored in the FALCAO database in a practical and optimized form.

The implementation of the FALCAO database occurred successfully and its existence leads to a considerably favorable situation. It is now essential to the routine of the researchers involved, not only due to the substantial improvement of the process but also to the confiability associated to it [6]. Fig. 6 shows the new Data Bank system.

Fig. 3. Data Bank system (control room)

C. Reactor Control Console Technology

The IEA-R1 reactor control console and control system were the result (1975) of evolutionary improvement based on experience with the design, construction, and installation of more than 50 research reactor instrumentation systems since 1958, and on the experience gained in operating reactors at General Atomics Company-GA (San Diego, CA, USA) over a similar period. All instrument components were of high quality industrial grade and-or meet military specifications. Fig. 4 shows the reactor control room.

Fig. 4. Reactor control room

All active components used in the modules were solid state devices for high reliability and “reduced size”. Some integrated circuits were used extensively where appropriate, with printed circuit boards of high temperature and fire-resistant material.

All channels provide trip inputs to the protective system and display channel outputs on analog meters calibrated in percent power. Fig. 5 shows the control desk.

Fig. 5. Control desk components

1) *Actual control console*

All function essential to operation of the reactor are controlled by the operator from a desk-type control console located in the room (separated by a concrete wall and a lead glass window for visualization) near the reactor (located located in the swimming pool hall). Instrumentation contained in the console is connected by means of special circuits to control rod drives, facility interlock system, and various detectors positioned around the reactor core. Reactor power is regulated by operation of neutron-absorbing rods. These shim rods are actuated by lighted pushbutton switches on the control panel. For each shim rods there is a DOWN and an UP switch to operate the drive motor; the annunciator light under the pushbutton switch illuminates if the rod reaches the full up position, or the full down position. Rod position is read on a digital position indicator (synchro-resolver module) for each drive.

2) *Start-up channel*

This channel consists of a ten-decade NLL-2 wide range logarithm and linear channel (S1). This channel uses counting and Campbell techniques to produce an accurate reading of log power over ten decades, even in the presence of high gamma background of 10^6 R.hr^{-1}. It operates from a special fission chamber. The output of the log power channel is displayed on analog meter and on a dual-pen recorder mounted in the front of the console. Period information is also derived from the log power channel and displayed on a front panel meter (left hand control desk).

3) *Safety channels.*

The three safety channels are all solid-state high reliability current amplifier. The channels receive current inputs from separated neutron detectors. The channels use soli state amplifier feeding bistable trip circuits. One channel is read on the left hand panel (drawer) and the other two on the right hand panel. All channels provide trip inputs to the calibrated in percent power.

4) *Period channel*

The log-n amplifier produces voltage proportional to the logarithm of neutron flux. A derivative circuit produces a voltage proportional to the inverse of reactor period, which is then amplified by an operational amplifier and displayed on a control panel meter that is calibrated in seconds (-30 to +3 sec), adjusted for 12 seconds in IEA-R1 reactor case.

5) *Reactor automatic control*

In automatic mode of operation the flux controller (Linear Channel) operates as an automatic reactor control system. A comparator circuit, the regulator module, is used in regulating reactor power to a preset value established by the operator (Demand). The flux controller compares the output signal of the Linear Channel with a demand power signal and adjusts the regulating rod position in an appropriate direction to compensate for any difference in power signal. Period information is used to automatically limit the maximum rate of change in reactor power to a preset period (12 seconds). All of the linear power channels have solid state bistable trip units on their outputs which feed trip signals to the scram logic system (Interlock System-IS). These bistables may be adjusted over the entire range to trip at any power level. The logic system is a two of three (2to3) system gate which will produce reactor scram upon trip of any two of these bistables. Fig. 6 shows the left and right panels of control desk.

Fig. 6. Left and right hand panels control desk

V. PROPOSAL FOR A NEW CONTROL CONSOLE

The need to change the reactor instrumentation came four years ago due to corrective maintenance of electronic modules of control desk, deterioration of passive and active electronic components (heat and humidity) as well as mechanical failures of pushbuttons, connectors, wires and signal and control cables after 30 years of continuous operation of the reactor.

After a detailed study of nuclear electronic components suppliers in the international market the IEA-R1 reactor I&C Division concluded that an ordering of a new control console was mandatory in a short term. The new instrumentation and reactor control desk should use modern components for data acquisition and processing of operational data to be used for nuclear parameters monitoring and power reactor control

A. *Data Acquisition Components*

In the past two decades, advances in programmable device technologies, in both the hardware and software arenas, have been extraordinary. The original application of rapid prototyping has been complemented with a large number of new applications that take advantage of the excellent characteristics of the latest devices. High speed, very large number of components, large number of supported protocols, and the addition of ready-to-use intellectual property cores make programmable devices the preferred choice of implementation and even deployment in mass production quantities [7].

Data acquisition is a necessity, which is why data acquisition systems and software applications are essential tools in a variety of fields. For instance, research scientists rely on data acquisition tools for testing and measuring their laboratory-based projects. Therefore data acquisition system designers must have an in-depth understanding of each part of the systems and programs created. Fig. 7 shows a proposal of a digital data acquisition from General Atomic adapted to IEA-R1 reactor instrumentation.

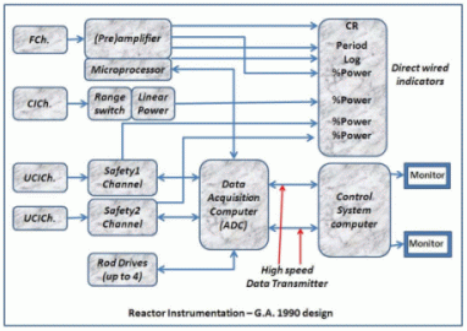

Fig. 7. G.A. data acquisition based design [8]

Today's complicated physics experiments require highly complex data acquisition systems and software that are capable of managing large amounts of information. Many of the systems require high-speed connections and digital recording. And they must be reconfigurable. Signals that are hard to characterize and analyze with a real-time display are evaluated in terms of high frequencies, large dynamic range, and gradual changes.

Well-designed data acquisition and control software should be able to quickly recover from instrumentation failures and power outages without losing any data. Data acquisition software must provide a high-level language for algorithm design. Moreover, it requires data-archiving capability for verifying data integrity.

A data acquisition system's complexity tends to increase with the number of physical properties it must measure. Resolution and accuracy requirements also affect a system's complexity. To eliminate cabling and provide for more modularity, data acquisition capabilities and signal conditioning in one device can be combined.

Electrical isolation is also an important topic. The goal is to eliminate ground loops (common problems with single-ended measurements) in terms of accuracy and protection from voltage spikes.

For all of the aforementioned reasons, field-programmable arrays (FPGAs) will figure prominently in the evolution of data acquisition system technology. The flexibility of FPGAs makes them ideal for custom data acquisition systems and embedded applications [9].

B. The FPGA Option

The field-programmable gate array (FPGA) is a semiconductor device that can be programmed after manufacturing. Instead of being restricted to any predetermined hardware function, an FPGA allows you to program product features and functions, adapt to new standards, and reconfigure hardware for specific applications even after the product has been installed in the field—hence the name "field-programmable". FPGA can be used to implement any logical function that an Application-Specific Integrated Circuit (ASIC) could perform, but the ability to update the functionality after shipping offers advantages for many applications. Fig. 8 shows FPGA internal components.

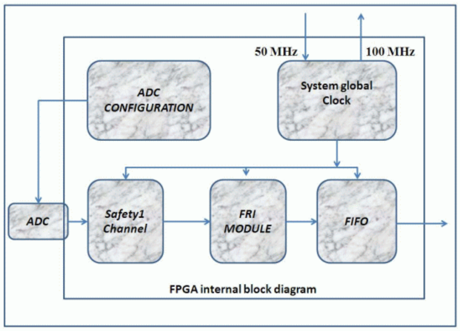

Fig. 8. FPGA internal block components [10]

As FPGAs continue to evolve, the devices have become more integrated. Hard intellectual property (IP) blocks built into the FPGA fabric provide rich functions while lowering power and cost and freeing up logic resources for product differentiation. Newer FPGA families are being developed with hard embedded processors, transforming the devices into systems on a chip (SoC).

FPGA chip adoption across all industries is driven by the fact that FPGAs combine the best parts of application-specific integrated circuits (ASICs) and processor-based systems. These benefits are: a) Faster I/O response times and specialized functionality, b) Exceeding the computing power of digital signal processors, c) Rapid prototyping and verification without the fabrication process of custom ASIC design, d) Implementing custom functionality with the reliability of dedicated deterministic hardware and e) Field-upgradable, eliminating the expense of custom ASIC re-design and maintenance [11].

Fig. 9 shows an example (monitor screens) of the new reactor control console: Start-up, Safety, Period, N-16 and Delta-P channels are at left hand panel; Linear (automatic control) channel is at the center and Process parameter signals (Temperature, Primary and Secondary Flows, Level and others) are at right hand panel. All parameters must be controlled through computer keyboard, manual control pushbuttons and shim rods position indicators remain the same.

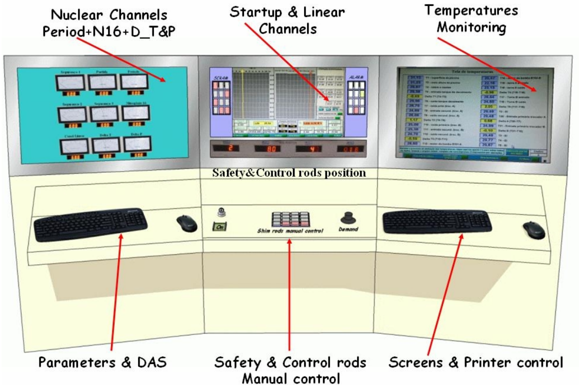

Fig. 9. Operational lay-out of a new control console

VI. RESULTS

The Pumps Vibration Monitoring System results shown that, for the specific case of the motor-pumps of IEAR1 nuclear research reactor, although the technique using the envelope of acceleration, which is not available in the current system used to monitor the vibration of the motor-pumps, is the one with best performance, the other techniques available in the system are sufficient to monitor the four types of mechanical problems mentioned.

The implementation of FALCAO Data Bank System occurred successfully and its existence leads to a considerably favorable situation. It is now essential to the routine of the researchers involved, not only due to the substantial improvement of the process but also to the confiability associated to it.

After a detailed study of nuclear electronic components suppliers in the international market the IEA-R1 Research Reactor Center concluded that an ordering of a new control console is mandatory in a short term. The new instrumentation and reactor control desk should use modern components for data acquisition and processing of operational data to be used for nuclear parameters monitoring and power reactor control.

VII. CONCLUSIONS

The vibration monitoring pumps system was chosen because they were considered important for safety and availability of the facility. Also, reviewing the primary pumps maintenance history, one can observe that these pumps present high frequency of corrective maintenance indicating that predictive and preventive maintenance as well as testing and inspection are not effective.

The database FALCAO is indispensable to the daily life of these researchers, due to the substantial improvement of current processes, when compared to previous processes to the database FALCAO. The most significant factor of improvement is less time spent on the acquisition of information, coupled with the versatility and reliability that the SACD system features provide. Currently the bank FALCAO provides information of last five years of operation of the IEA-R1 and is also properly sized to receive data in the same order over the next four years.

To add capability to on-line monitoring and detection of early faulty sensors, equipment and systems, the most effective way is through a plant condition on-line monitoring system. Therefore, it is advised that this system be upgraded to include artificial intelligence capability.

At the present time there are three international proposals to be study for a new IEA-R1 instrumentation control console. Each one will be studied to decide the more convenient project to reactor necessities.

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