ON-LINE MEASUREMENT OF THE REACTIVITY TEMPERATURE COEFFICIENT OF THE IPR-R1 TRIGA NUCLEAR RESEARCH REACTOR

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Abstract. *On-line monitoring of several new process variables of the IPR-R1 TRIGA Reactor of the Nuclear Technology Development Center – CDTN became possible after the data acquisition and processing system implementation and the installation of one instrumented fuel rod in the reactor core. Several neutronic and thermo-hydraulic parameters are now registered, such as the operation power, the reactivity insertion in the core, the control rod position, the fuel and the water temperatures, and so on. Since the inherently safe operation of a reactor is dependent on the reactivity control, it is essential to have information about this parameter over many different temperature ranges. The fuel elements have been designed to provide a significant prompt negative temperature coefficient that allow safe reactor operation. The developed monitoring system gives, in real time, the reactivity temperature coefficient. The system gives also others reactor parameters such as: reactivity worth of the control rods, when the rod considered is inserted or withdrawn in the core and also the loss of reactivity during the reactor operation. This paper describes the methodology and the results in on-line monitoring of the temperature coefficient of the IPR-R1 TRIGA Reactor.*

Keywords: *TRIGA nuclear reactor, instrumented fuel element, reactivity, temperature, core.*

1. INTRODUCTION

Reactivity is the most important parameter in nuclear reactor operation. When it is positive the reactor is supercritical, zero at criticality, and negative the reactor is subcritical. Reactivity can be controlled in various ways: by adding or removing fuel; by changing the fraction of neutrons that leaks from the system; or by changing the amount of an absorber that competes with the fuel for neutrons. In a nuclear reactor, temperature changes can introduce reactivity changes. This property is called the "temperature coefficient of reactivity." In water-cooled nuclear reactors, the predominant reactivity changes are brought about by changes in the temperature of the coolant water. In this case the temperature coefficient is negative, which means that an increase in coolant temperature causes a decrease in reactivity, and vice-versa. A reactor with a negative temperature coefficient of reactivity is therefore inherently self-controlling and safe. The TRIGA reactor (Training, Research, Isotopes, General Atomics) uses uranium-zirconium hydride (UZrH) fuel, which has a large, prompt negative thermal coefficient of reactivity, meaning that as the temperature of the core increases, the reactivity rapidly decreases — so it is highly unlikely, though not impossible for a meltdown to occur.

The IPR-R1 TRIGA Nuclear Research Reactor, shown in Fig. 1, is a pool type reactor cooled by natural circulation. The core consists of a lattice of cylindrical fuel-moderator elements and graphite elements. The 250 kW core configuration has 63 fuel elements composed of 58 original aluminum clad elements and 5 fresh stainless steel clad fuel elements. The elements are arranged in five concentric rings, and the spaces between the rods are filled with water that acts as coolant and moderator. The power level of the reactor is controlled with three control rods: a Regulating rod, a Shim rod, and a Safety rod. Fuel temperature was obtained through the use of an instrumented fuel element with thermocouples embedded in the zirconium centerline pin. Fuel temperature measurements were taken in the position B1 (ring B). The inlet and outlet coolant temperatures were measured by using two type K thermocouples inserted in two channels in the core, close to the position B1. A schematic view of the present core configuration is shown in Figure 2. TRIGA reactor utilizes solid fuel elements in which the zirconium-hydride moderator is homogeneously combined with 20 %-enriched uranium (^{235}U). The feature of these fuel-moderator elements is the prompt negative temperature coefficient of reactivity, which automatically limits the reactor power to a safe level in the event of a power excursion. Because of this coefficient, a significant amount of reactivity is needed to overcome the temperature and allow the reactor to operate at high power levels. During steady-state operation, the reactivity in the reactor core is controlled by three independent control rods and drives.

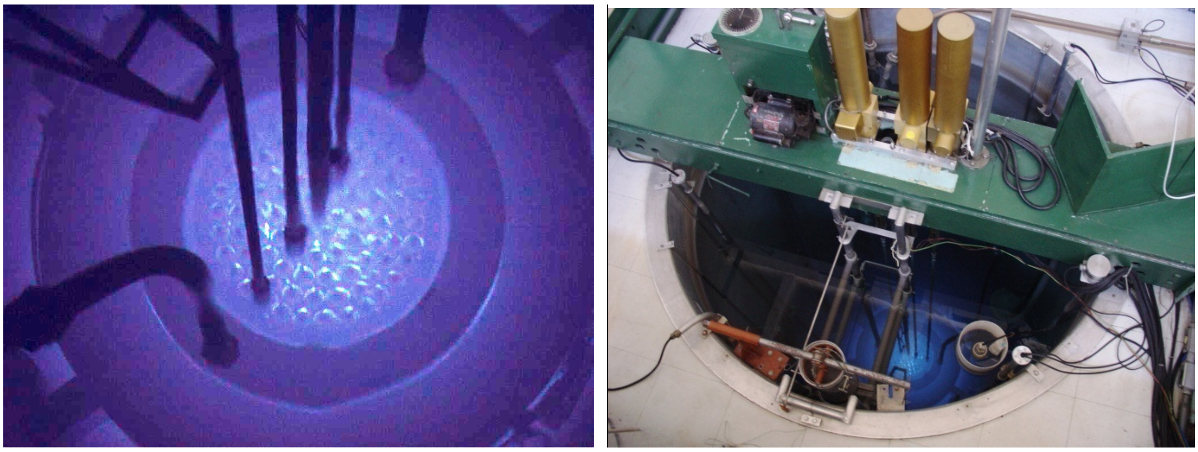


Figure 1. Core upper view and pool of the IPR-R1 TRIGA

Nuclear reactors must have sufficient excess reactivity to compensate the negative reactivity feedback effects such as those caused by the fuel temperature and power defects of reactivity, fuel burnup, fission poisoning production, and also to allow full power operation for predetermined period of time. To compensate for this excess reactivity, it is necessary to introduce an amount of negative reactivity into the core which one can adjust or control it at will. In the IPR-R1 reactor the reactivity control is done by three control rods that can be inserted into or withdrawn from the core.

The data acquisition system used in the IPR-R1 Reactor consolidates the information about the reactor status and provides an on-line data analysis (Mesquita e Rezende, 2004). The data acquisition program attends to the recommendations of the International Atomic Energy Agency (IAEA, 2002). It will be shown here the methodology used to find the equations that were used in the data acquisition program to monitor, in real-time, the control rods worth, the reactor temperature coefficient of reactivity and the loss of reactivity during the reactor operation.

2. CONTROL RODS WORTH

The determination of the reactivity worth of individual control elements and the effects of such elements on the power distribution in the core is important to the safe and efficient operation of a nuclear reactor. Once a control rod is calibrated, it is possible to evaluate the magnitude of other reactivity changes by comparing the critical rod positions before and after the change. All three-control rods are calibrated by the positive period method. The method consists of withdrawing the control rod from a known critical position through a small distance. This adds a positive reactivity to the system and the reactor power increases in a exponential manner with time, and establishes a stable period that is measured using the doubling time, that is the time required for the power to increase by a factor of two. Each successive step is compensated by lowering the other control rod just enough to reestablish criticality. The reactivity associated with the measurement **is** gotten from the graphical form of the inhour equation, that gives the relationship between reactivity and the stable reactor period.

The experimental data obtained in (Souza *et al*., 2004), and the integral fitted worth curves of the Regulating, Shim and Safety control rods as a function of their positions are shown graphically in Fig. 3, Fig. 4 and Fig. 5, respectively. The equations representing the fitted model, and the coefficients of determination R^2, that confirm the goodness of the fit are also shown in the figures. The integral control rod worth curve is particularly important in research reactor operation. The equations were added to the data acquisition program.

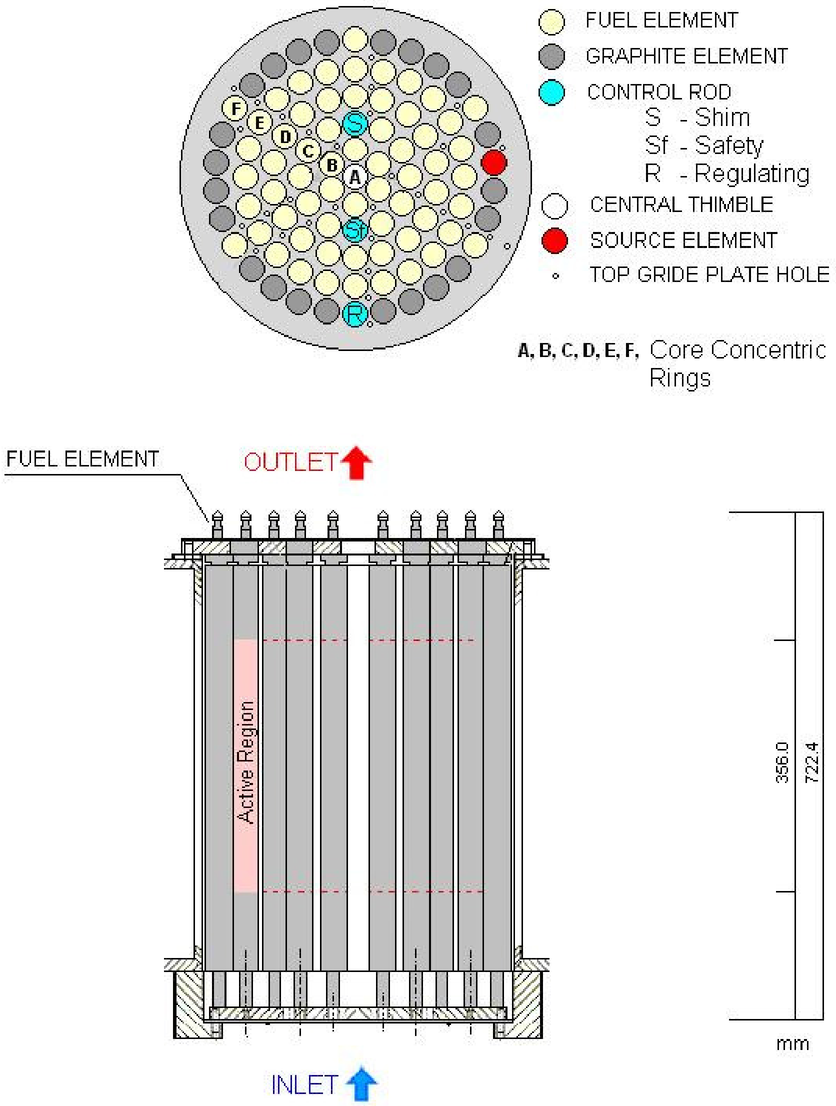


Figure 2. Core configuration of the IPR-R1 TRIGA Reactor

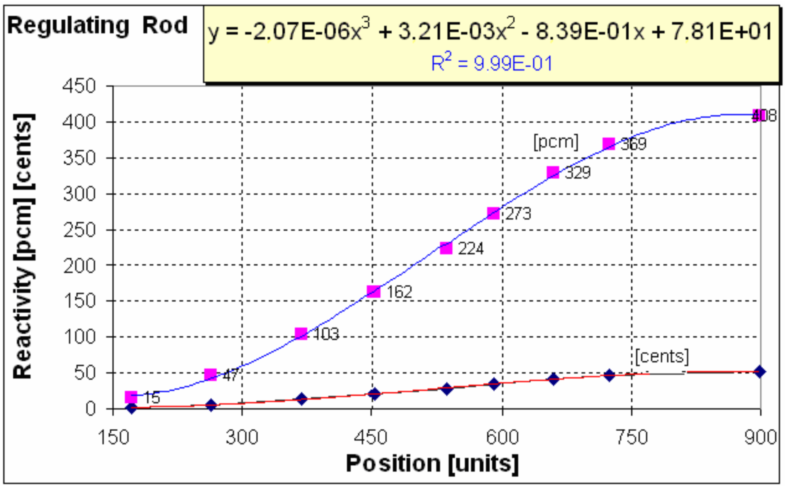


Figure 3. Reactivity as function of insertion of Regulation control rod

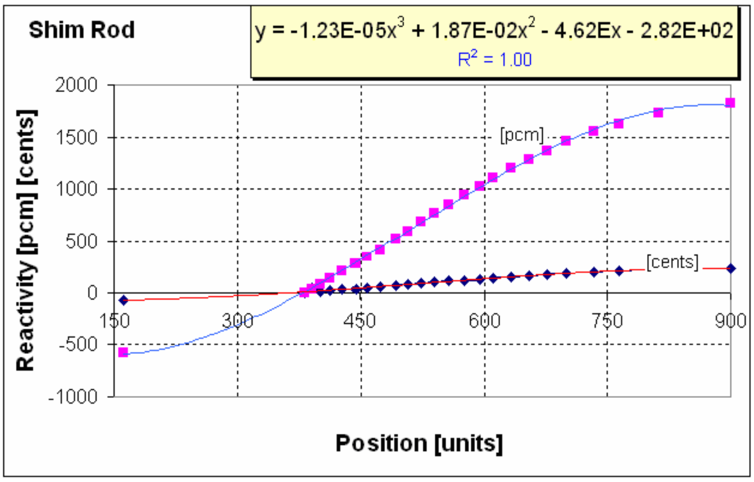


Figure 4. Reactivity as function of insertion of Shim control rod

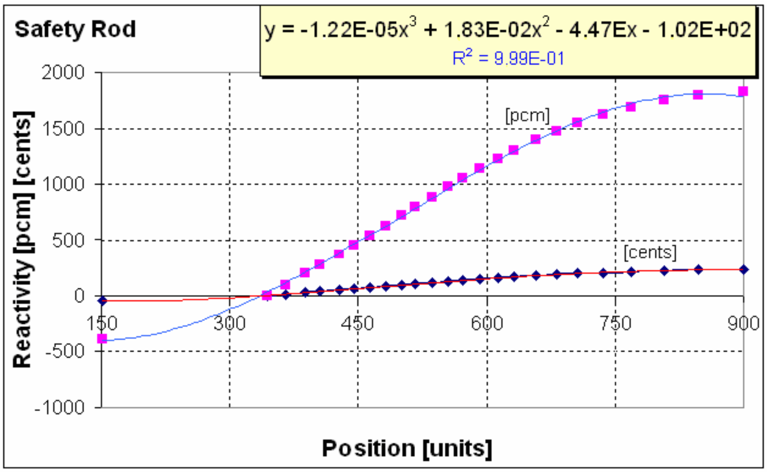


Figure 5. Reactivity as function of insertion of the Safety control rod

3. THE OVERALL TEMPERATURE COEFFICIENT OF REACTIVITY

The prompt temperature coefficient of reactivity is a very important safety parameter of research reactors, it is defined as the change in reactivity for a unit change in the fuel system temperature. A negative temperature coefficient of reactivity is desirable since it tends to counteract the effects of transient temperature changes during reactor operation. In TRIGA reactors the moderator is the hydrogen that is mixed with the fuel itself. If the fuel temperature increases when the control rods are suddenly removed, the neutrons inside the hydrogen-containing fuel rod become warmer than the neutrons outside in the cold water. These warmer neutrons inside the fuel cause less fissioning in the fuel and escape into the surrounding water. The end result is that the reactor automatically reduces the power within a few thousandths of a second, faster than any engineered device can operate. The inherent safety of the TRIGA reactor arises from the prompt negative temperature reactivity coefficient, whose measured value was (-1.1 ± 0.2) ¢/ºC (Souza et al., 2002), which effectively limits the power when excess reactivity is suddenly inserted.

The overall temperature reactivity coefficient of the reactor refers to the change in the total core temperature**.** Fuel temperatures were measured by three thermocouples in the center of the instrumented fuel element at location B1. This location is the hottest position in the core. To obtain the overall temperature coefficient it is necessary to know the average temperature in the core. This value was found using the temperatures distribution in the core shown in Fig. 6 (Mesquita, 2005). The average temperature as function of the maximum temperature in the core rings follows the equation shown in Fig. 7. The axial temperature distribution in the fuel follows the same distribution of neutron flux, maximum/average = 1.25 (Fig. 8). The average radial temperature distribution inside the fuel, in several operation power, is approximately 1.11 (Fig. 8). The equations found were added to the data acquisition program.

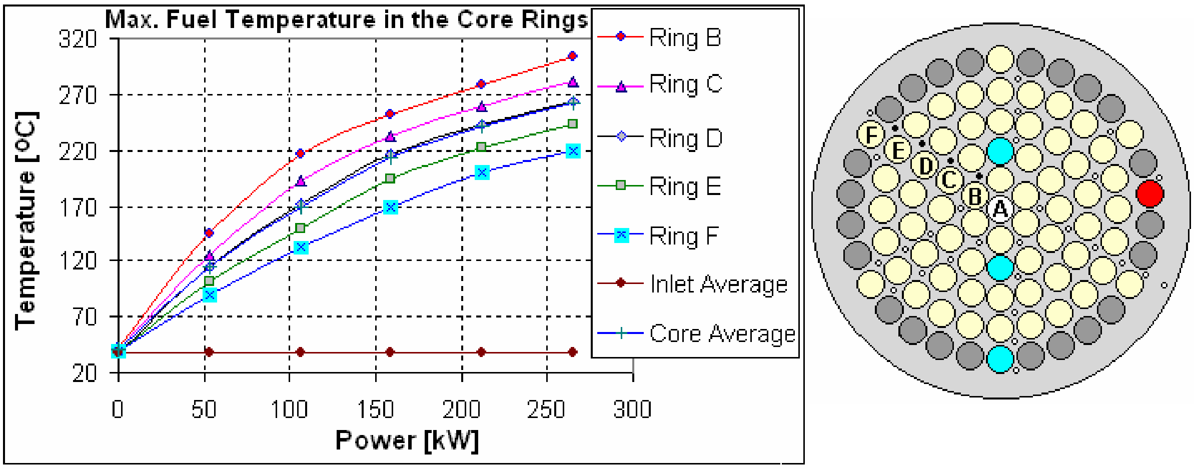


Figure 6. The IPR-R1 temperature distribution in the core rings

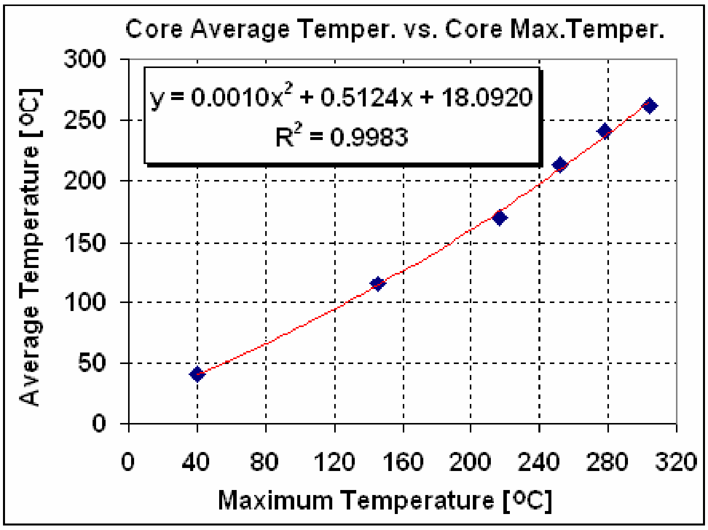


Figure 7. Core average temperature as function of core maximum temperature

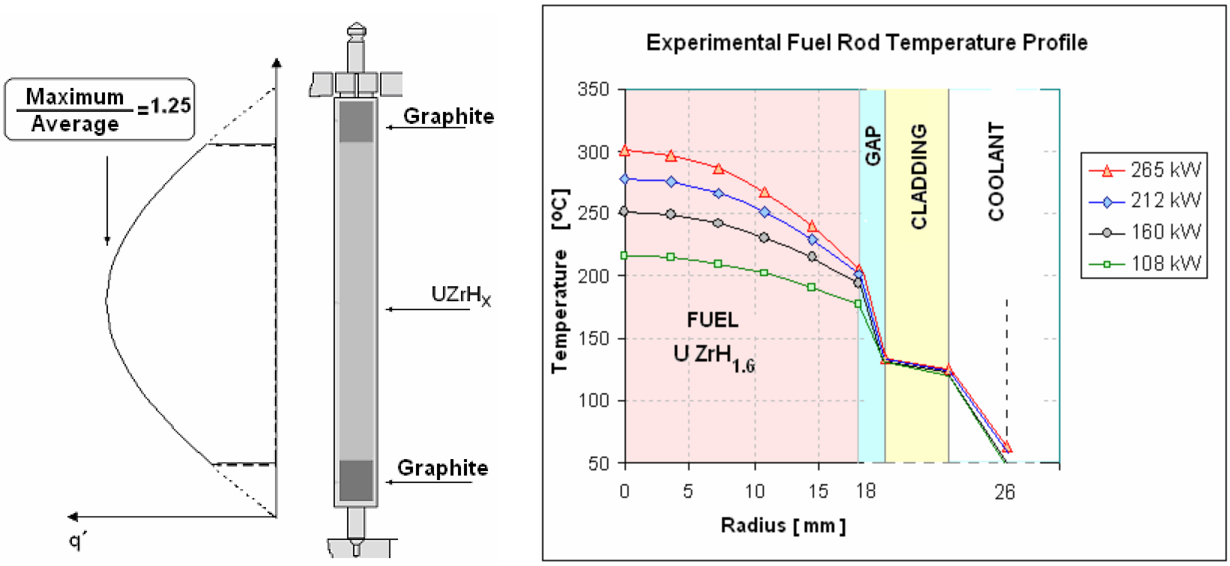


Figure 8. Experimental axial and radial fuel rod temperature profile

In other to obtain the power effects on the reactivity in the reactor it was performed the following experiment. The reactor power was increased, and, consequently, the fuel temperature, by withdrawing the Shim control rod in steps. All other control rods were completely withdrawn. The power increased with each increasing step, then reached a new, steady, higher level. The reactivity was determined from the calibrated Shim rod curve (Fig. 4), considering each critical rod position. The forced reactor cooling system was not operating during the experiment, and the initial fuel and water temperature at zero power was 24 ºC. Table 1 presents the experimental results, and Fig. 9 shows the curve and equation of the total temperature reactivity coefficient versus the core average temperature.

Table 1. Experimental results.

Reactor Power (kW)	**Fuel Temp. Max. (º C)**	**Core Temp. Average (º C)**	**ΔT (º C)**	**$\Delta\rho$ (cents)**	**$\Delta\rho/\Delta T$ (cents/º C)**
0.01	24.3	24.3		0.0	
5.3	40.8	29.3	5.0	-7.0	-1.40
17.0	59.2	37.4	8.1	-10.5	-1.29
21.2	67.0	41.0	3.6	-3.5	-0.97
40.3	94.3	54.3	13.3	-14.5	-1.09
66.8	129.0	72.7	18.4	-16.5	-0.90
111.3	185.5	106.3	33.7	-27.0	-0.80
154.8	225.8	133.2	26.8	-26.5	-0.99
208.8	251.7	151.7	18.5	-29.5	-1.60
238.5	263.5	160.4	8.7	-14.0	-1.60
254.4	269.4	164.8	4.4	-7.0	-1.57
262.9	271.4	166.4	1.5	-3.5	-2.31

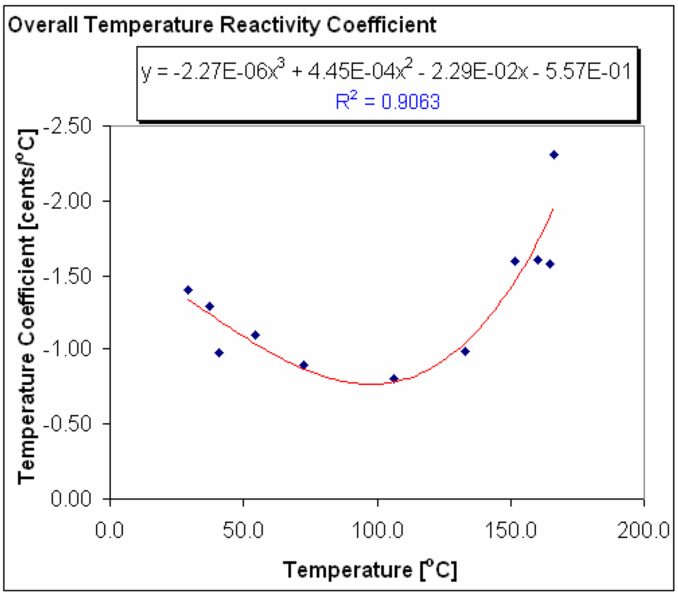


Figure 9. Overall temperature reactivity coefficient

Figure 10 shows the core reactivity evolution as a function of the fuel temperature (Mesquita, 2005), and Fig. 11 presents the associated reactivity loss to achieve a giving power level (Souza, *et al.*, 2006).

The equations of the control rods reactivity as function of their positions in the core, and the core reactivity as function of the temperature and the operation time were added to the data acquisition program. Figure 12 shows the acquisition system screen where the operator can monitor, during the reactor operation, the consolidated reactivity information.

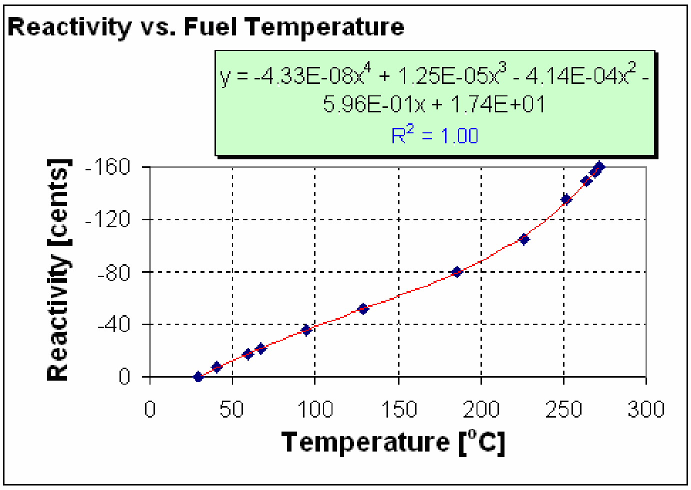


Figure 10. Change in reactivity as function of fuel temperature

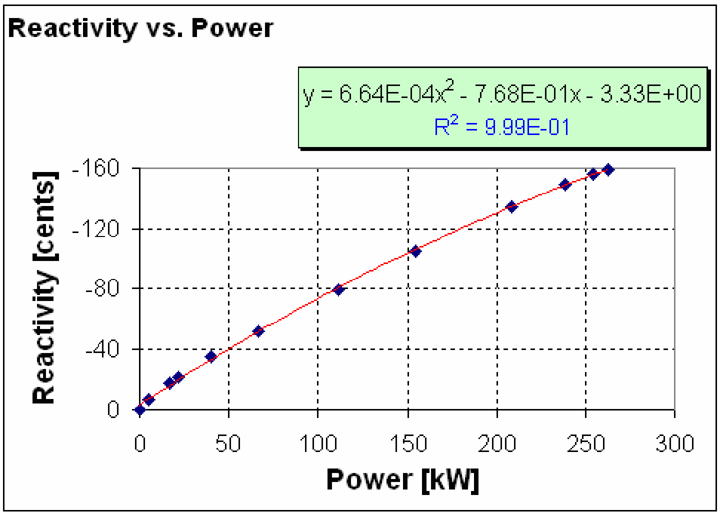


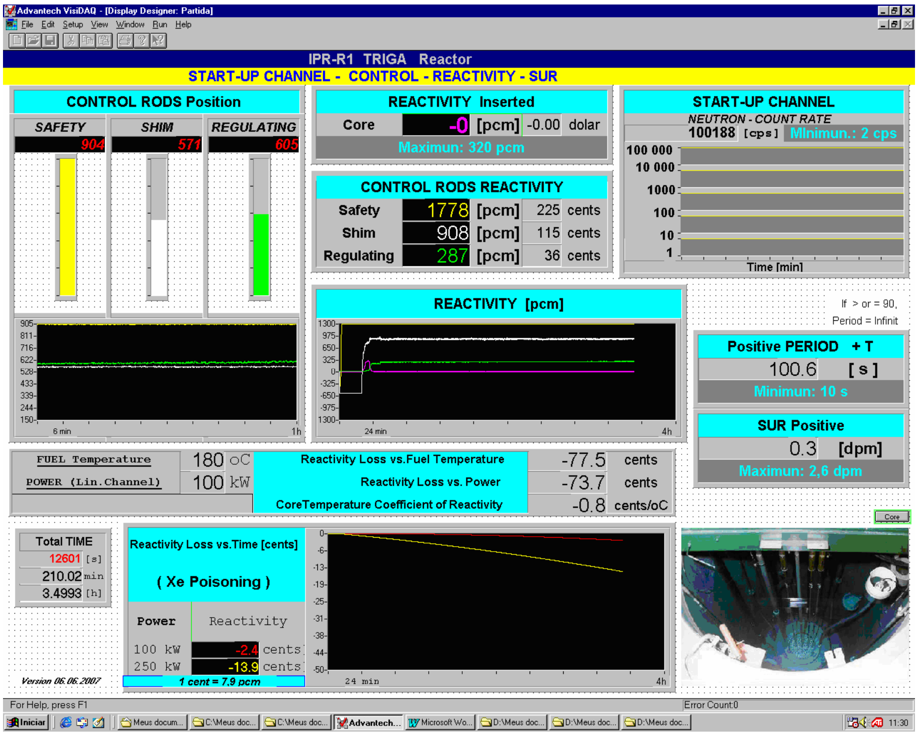
Figure 11. Change in reactivity as function of reactor power

4. CONCLUSIONS

The control of reactivity is one of the most important items that must be performed to ensure the safe and efficient operation of a nuclear research reactor. The reactor operators need to know, in real-time, the basic reactor behavior in order to understand and safely operate a nuclear reactor.

The data acquisition system has been designed and developed to automatically monitor and record all operational parameters of the IPR-R1 TRIGA Reactor. The color monitor provides on-line information about important operating parameters such as: the control rods positions; the control rods worth; the reactivity inserted in the core; the loss of reactivity caused by the fuel temperature, the reactor operation graphics, etc. Hard copies of the displays can be made using the graphics printer. The records of the reactor process variables are important for immediate or subsequent safe analyze, and for reporting the reactor operations to the organization and to external authorities (IAEA, 1995). The system does not propose to control the reactor operation, but to help the operator to get more information about the safety status of systems, and, if necessary, to be used to identify manual actions. The data acquisition and processing system implemented in the IPR-R1 TRIGA Reactor is the beginning of the control and instrumentation update to this reactor. In the future all the reactor operation will be made automatically by programmable logical controllers (PLC's), like other modern research and power reactors (Mizuki et al, 1995 and Swaminathan, 2005).

The overall temperature coefficient of reactivity presented in this work is a preliminary result. The uncertainty of this parameter is about ± 15%, mainly due to the uncertainty in power calibration of the reactor, which estimated value is ± 7.2% (Mesquita et al., 2007).



SAFETY 904
SHIM 571
REGULATING 605

REACTIVITY Inserted
Core -0 [pcm] -0.00 dolar
Maximun: 320 pcm

CONTROL RODS REACTIVITY
Safety 1778 [pcm] 225 cents
Shim 908 [pcm] 115 cents
Regulating 287 [pcm] 36 cents

START-UP CHANNEL
NEUTRON - COUNT RATE
100188 [cps] MInimun.: 2 cps

Positive PERIOD + T
100.6 [s]
Minimun: 10 s

SUR Positive
0.3 [dpm]
Maximun: 2,6 dpm

FUEL Temperature 180 oC
POWER (Lin.Channel) 100 kW
Reactivity Loss vs.Fuel Temperature -77.5 cents
Reactivity Loss vs. Power -73.7 cents
CoreTemperature Coefficient of Reactivity -0.8 cents/oC

Total TIME
12601 [s]
210.02 min
3.4993 [h]

Reactivity Loss vs.Time [cents]
(Xe Poisoning)

Power	Reactivity
100 kW	-2.4 cents
250 kW	-13.9 cents

1 cent = 7,9 pcm

Figure 12. Reactivity monitoring on the screen of the data acquisition system

3. ACKNOWLEDGEMENTS

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