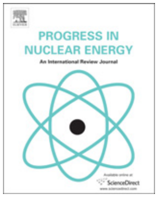
Progress in Nuclear Energy 52 (2010) 292–297

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene



On-line monitoring of the IPR-R1 TRIGA reactor neutronic parameters

Amir Zacarias Mesquita*, Rose Mary Gomes do Prado Souza

Centro de Desenvolvimento da Tecnologia Nuclear – CDTN, Campus da UFMG – Pampulha, P.O. Box: 941, 30.123-970 Belo Horizonte, MG, Brazil

Keywords:
TRIGA research reactor
Reactivity
Control rods worth
Fuel temperature

ABSTRACT

The 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 neutronics and thermo-hydraulics 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 on this parameter over many different temperature ranges. The fuel elements have been designed to provide a significant negative prompt temperature coefficient that allows safe reactor operation. The developed monitoring system gives the reactivity worth of the control rods, when the rod considered is inserted into the core or withdrawn from it, and also the loss of reactivity during the reactor operation. This paper describes the methodology and the results found with the on-line monitoring of the reactivity behavior of the IPR-R1 TRIGA Reactor.

1. Introduction

The IPR-R1 TRIGA Nuclear Research Reactor is a pool type reactor cooled by natural circulation, and having as fuel an alloy of zirconium hydride and uranium enriched at 20% in ^{235}U.

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 information about the reactor status and provides an on-line data analysis (Mesquita and Rezende, 2004). The data acquisition program responds 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 knowledge of the reactor's response to specific control rod motions is essential to the safe and efficient operation of a nuclear reactor. The effectiveness, or worth, of a control rod depends largely upon the value of the neutron flux at the location of the rod. Fig. 1 presents a top view of the IPR-R1 core configuration, and the Regulating, Shim and Safety control rod positions.

All three control rods were calibrated by the positive period method that consists of withdrawing the control rod from a known critical position through a small distance, and then to measure the stable period of the resultant reactor transient. The period was obtained 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. In this process the control rod under calibration proceeds from the most inserted position (maintaining the reactor critical) to fully removed. The Safety and Shim rods were intercalibrated. The idea was to measure one control rod in presence of another rod, used for compensating the reactivity introduced by step withdrawal of the measure rod. The reactivity measurements were performed at a low power so the temperature increase during the experiment was negligible. The reactivity values associated with the periods obtained were gotten from the graphical form of the inhour equation.

The experimental data obtained in (Souza et al., 2002), and the integral fitted worth curves of the Regulating, Shim and Safety

---

* Corresponding author. Tel.: +55 31 3069 3309; fax: +55 31 3069 3380.
E-mail address: amir@cdtn.br (A.Z. Mesquita).

0149-1970/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pnucene.2009.05.006

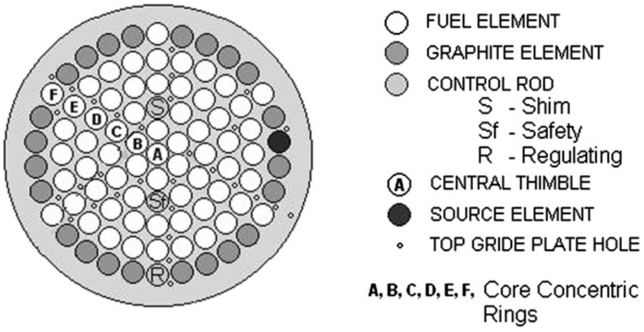


Fig. 1. Core configuration of the IPR-R1 TRIGA Reactor.

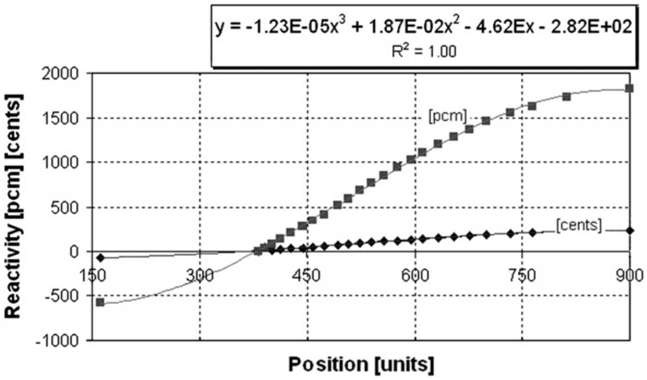


Fig. 3. Experimental integral Shim control rod worth curve.

control rods as a function of their positions are shown graphically in Figs. 2–4, 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 equations were added to the data acquisition program. The integral control rod worth curve is particularly important in research reactor operation. The measured values of the Regulating, Shim and Safety control rod worth were 0.5, 3.1 and 2.8 cents, respectively (Souza et al., 2002).

3. Coefficients of reactivity

Temperature is one of the operating conditions that affect the reactivity of a reactor core. Such reactivity variation with temperature is the principal feedback mechanism determining the inherent stability of a nuclear reactor. The temperature coefficient of reactivity is defined as the change in reactivity due to a variation in the average temperatures of each component of the core. A negative temperature coefficient of reactivity is desirable since it tends to counteract the effects of transient temperature changes during reactor operation. An increase in temperature will cause a decrease in the reactivity, hence a decrease in reactor power and temperature which tends to stabilize the reactor power level.

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 negative prompt temperature reactivity coefficient, whose measured value was (-1.1 ± 0.2) ¢/°C (Souza and Resende, 2004). The prompt temperature coefficient refers only to the fuel temperature, and the overall temperature 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, which 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. 5 (Mesquita, 2005). The average temperature as function of the maximum temperature in the core rings follows the equation shown in Fig. 6. The axial temperature distribution in the fuel follows the same distribution of the neutron flux, maximum/average = 1.25 (Fig. 7), and the radial temperature distribution inside the fuel, in several operation power, is approximately 1.11 (Fig. 7).

In the reactivity experiment, performed in (Souza et al., 2006), the reactor power was increased, and, consequently, the fuel temperature and the core 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

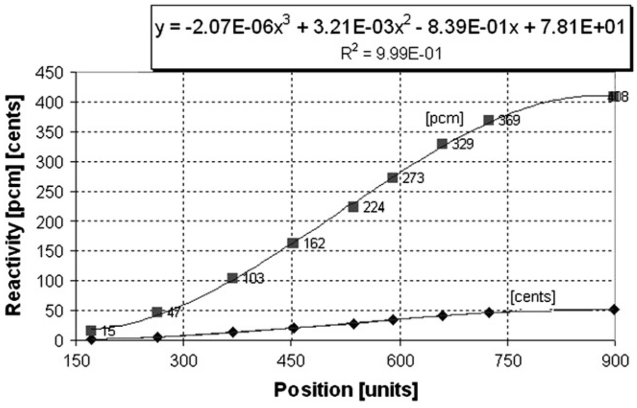


Fig. 2. Experimental integral Regulating control rod worth curve.

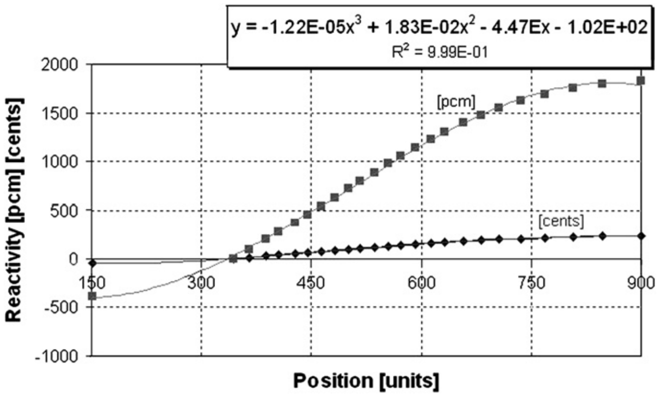


Fig. 4. Experimental integral Safety control rod worth curve.

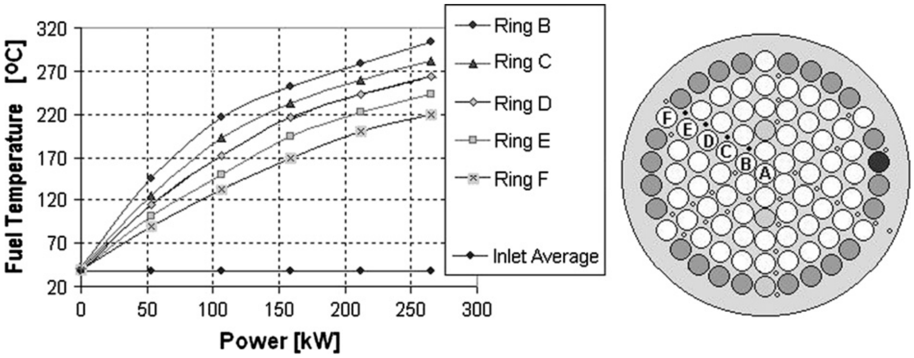


Fig. 5. The IPR-R1 temperature distribution in the core rings.

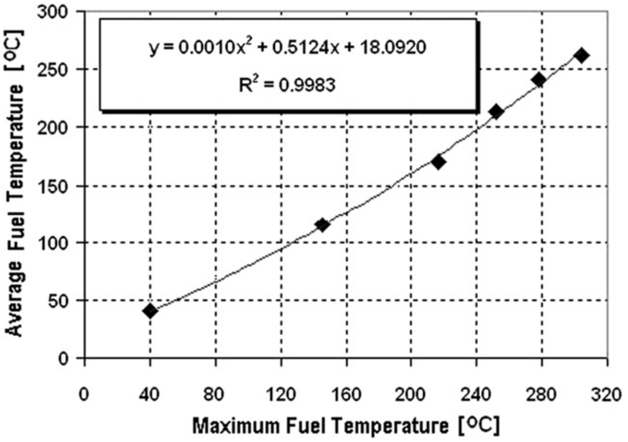


Fig. 6. Core average temperature as a function of core maximum temperature.

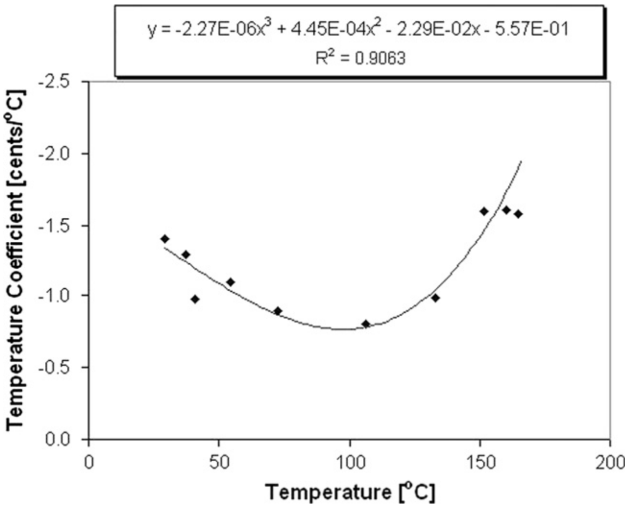


Fig. 8. Overall temperature reactivity coefficient.

from the calibrated Shim rod curve (Fig. 3), considering each critical rod position. The forced reactor cooling system was not operating during the experiment, and the initial fuel and water temperatures at zero power were 24 °C. Fig. 8 shows the experimental curve and equation of the total temperature reactivity coefficient versus the core average temperature, and the core reactivity evolution as a function of the fuel temperature is presented in Fig. 9.

Fig. 10 shows the power coefficient of reactivity as a function of the reactor power level, and Fig. 11 presents the associated reactivity loss to achieve a given power level (Souza et al., 2006). In the

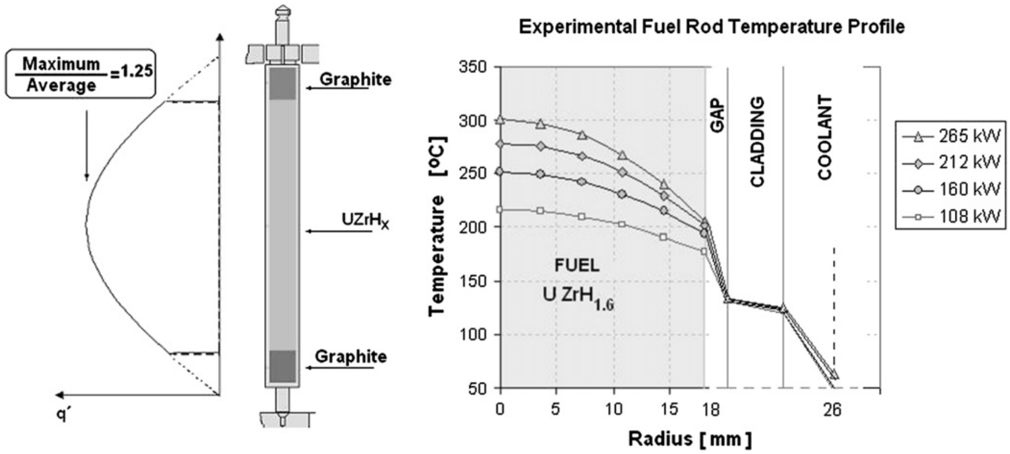


Fig. 7. Experimental axial and radial fuel rod temperature profiles.

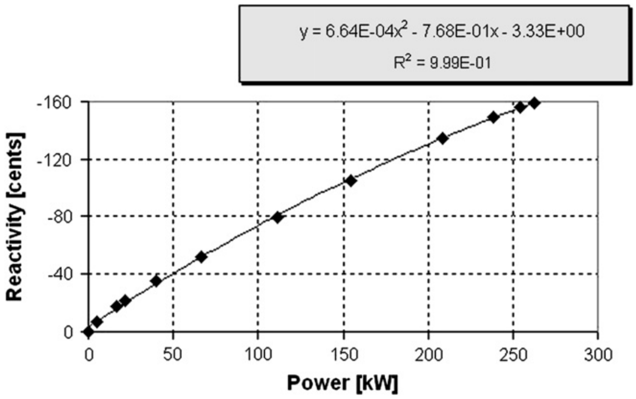


Fig. 9. Change in reactivity as a function of reactor power.

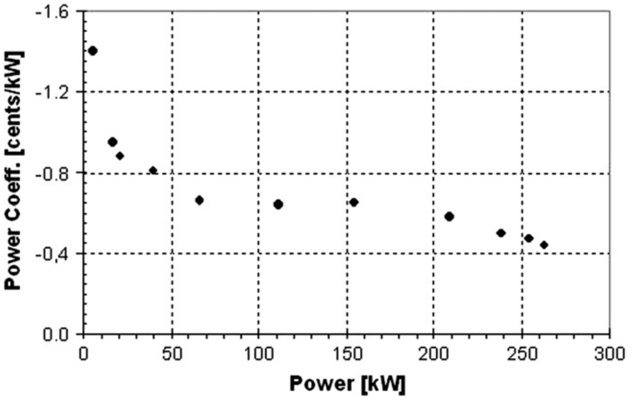


Fig. 10. Power coefficient of reactivity versus reactor power level.

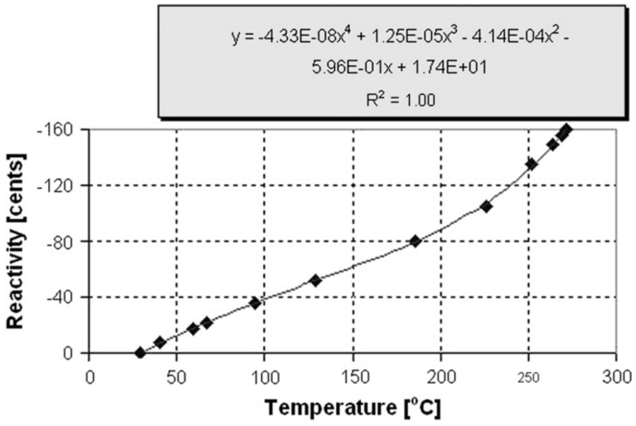


Fig. 11. Change in reactivity as a function of fuel temperature.

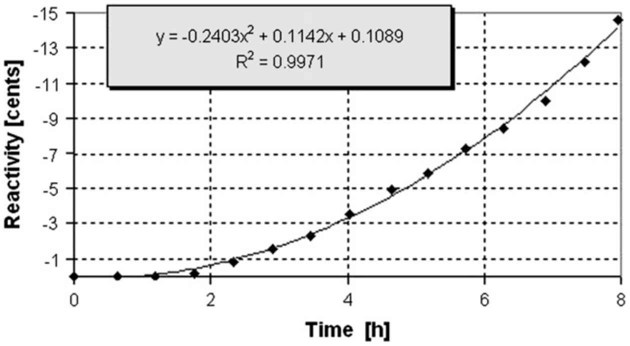


Fig. 12. Xenon poisoning during power operation at 100 kW.

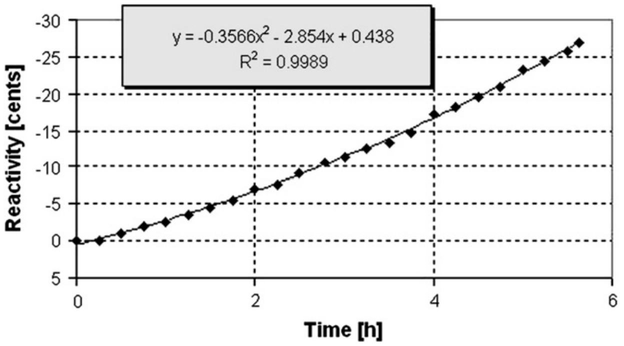


Fig. 13. Xenon poisoning during power operation at 250 kW.

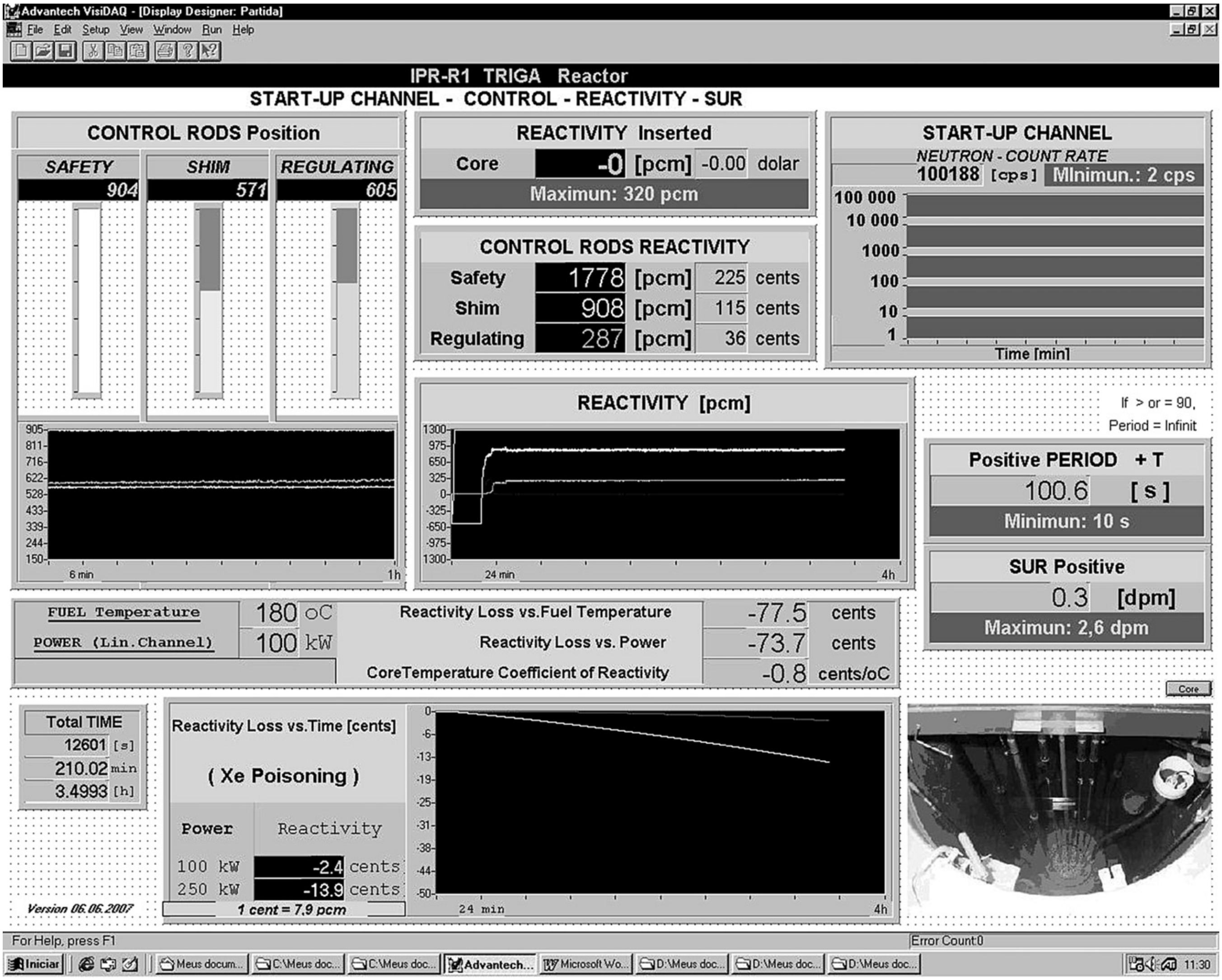
last figure the curve is almost linear and gives a power coefficient of, approximately, −0.65 cent/kW. Because of the prompt negative temperature coefficient, a significant amount of reactivity is needed to overcome temperature and allow the reactor to operate at higher power levels in steady state operation. The power defect, that is the change in reactivity taking place between zero power and full power, is around 1.6 $.

The purpose of these experiments was to measure the core temperature reactivity coefficient as a function of the core temperature and the loss of reactivity as a function of the fuel temperature and the reactor power. The equations founded were added to the data acquisition program.

4. Fission product poisoning

During the operation of a nuclear reactor many fission products are generated. The xenon-135 is the most significant of them because it acts as poison in the reactor, affecting the reactivity of the core, due its enormous thermal neutron absorption cross section. Fig. 12 shows the loss of reactivity caused by the ^{135}Xe poisoning during the reactor operation at 100 kW, and Fig. 13 shows the same loss at 250 kW (Souza et al., 2002). The two regression equations, added to the data acquisition program, and their coefficients of determination (R^2) are given in the figures.

Fig. 14 shows the acquisition system screen where the operator can monitor, during the reactor operation, the consolidated reactivity information.



IPR-R1 TRIGA Reactor

START-UP CHANNEL - CONTROL - REACTIVITY - SUR

CONTROL RODS Position

SAFETY	SHIM	REGULATING
904	571	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

REACTIVITY [pcm]

If > or = 90,
Period = Infinit

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

Version 06.06.2007

For Help, press F1

Error Count:0

Fig. 14. Reactivity monitoring on the screen of the data acquisition system.

5. Conclusions

The reactivity control 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 the 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 xenon poisoning and 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, 2002). The system does not propose to control the reactor operation, but to help the operator to get more information about the safety status of the 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 of this reactor. In the future all the reactor operation will be made by programmable logical controllers (PLCs), like other modern research and power reactors (Hai et al., 2003), (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).

Acknowledgments

The authors express their thanks to the IPR-R1 operational staff and to the *Fundação de Amparo à Pesquisa do Estado de Minas Gerais* (*FAPEMIG*) for the partial financial support.

References

Hai, T.D., et al., 2003. Construction of the Monitoring, Processing and Logging Systems Supporting for Management, Operation and Maintenance of the Dalat

Reactor Control System. Dalat Nuclear Research Institute. The Annual Report for 2003, VAEC, pp. 21–25.

IAEA, 2002. Instrumentation and Control Systems Important to Safety in Nuclear Power Plants. IAEA Safety Guide No. NS-G-1.3, Vienna.

Mesquita, A.Z., 2005. Experimental Investigation on Temperatures Distributions in a Research Nuclear Reactor TRIGA IPR-R1. Ph.D. thesis, Universidade Estadual de Campinas, São Paulo (in Portuguese).

Mesquita, A.Z., Rezende, H.C., Tambourgi, E.B., 2007. Power calibration of the TRIGA Mark I nuclear research reactor. Journal of the Brazilian Society of Mechanical Sciences and Engineering XXIX, 240–245.

Mesquita, A.Z., Rezende, H.C., 2004. Data acquisition system for TRIGA Mark I nuclear research reactor of CDTN. In: America Nuclear Energy Symposium (ANES 2004), Miami Beach, Flórida. America Nuclear Energy.

Mizuki, F., Miyamoto, Y., Seiji, T., 1995. Control and Instrumentation for ABWR Plant. 1:NUCAMM-90: Nuclear Power Plant Control Complex with Advanced Man–Machine Interface-90, pp. 164–167.

Souza, R.M.G.P., et al., 2002. Power Upgrade Tests of IPR-R1 TRIGA Reactor, NI-IT4–07/02. CDTN/CNEN, Belo Horizonte (in Portuguese).

Souza, R.M.G.P., et al. 2006. Reactivity power coefficient determination of the IPR-R1 TRIGA reactor. In: Proceedings of the Third World TRIGA Users Conference, Belo Horizonte.

Souza, R.M.G.P., Resende, M.F.R., 2004. Power upgrading tests of the TRIGA IPR-R1 nuclear reactor to 250 kW. In: Second World TRIGA Users Conference, Atominstitute Vienna, Austria.

Swaminathan, P., 2005. Design aspects of safety critical instrumentation of nuclear installations. International Journal Nuclear Energy Science and Technology 1 (2/3).