NEUTRONIC TESTS IN THE IPR-R1 TRIGA REACTOR

R.M.G.P. SOUZA, A.Z. MESQUITA
Nuclear Technology Development Centre/Brazilian Nuclear Energy Commission (CDTN/CNEN),
Campus da UFMG – Pampulha,
Belo Horizonte,
Brazil

Abstract

This paper presents the results of neutronic tests performed in August 2010 in the IPR-R1 TRIGA reactor, located at the Nuclear Technology Development Center — CDTN, Belo Horizonte, Brazil. These experiments follow the determination of the IPR-R1 Safety Analysis Report, which states the necessity to perform them annually to ensure the safety of the reactor. The IPR-R1 TRIGA reactor has a nominal power of 100 kW in a steady-state operation, and its power will be upgraded to 250 kW. The license to operate at 250 kW is under final review by the regulatory body of Brazil. The tests described here will be repeated and new experiments will be conducted in the new power. The control rods were calibrated and the worth of Regulation, Shim and Safety rods were 0.48 $, 3.21 $ and 2.84 $, respectively. The value of the excess reactivity obtained to compensate the negative reactivity due to negative temperature coefficient, xenon poisoning, etc, was 2.00 $. The shutdown margin obtained was 1.32 $, the power coefficient of reactivity was -0.66 ¢/kW, and the power defect was 0.76 $.

1. INTRODUCTION

The aim of this paper is to present the results of recent neutronic tests conducted in the IPR-R1 TRIGA reactor, as determined by the IPR-R1 Safety Analysis Report, which states the necessity to perform them annually to ensure the safety of the reactor [1]. The tests were performed to determine: the calibration of the control rods, the excess of reactivity, the shutdown margin, and the power defect. Finally, it was measured the reactivity loss of the core due to one operation at 100 kW, during eight hours. It was confirmed the necessity of new fuel elements in the core to operate the reactor at the new power (250 kW) [2, 3].

2. THE IPR-R1 REACTOR

The IPR-R1 TRIGA reactor is a pool type research reactor moderated and cooled by light water. The fuel is a solid, homogeneous mixture of U-ZrH alloy containing 8.5% and 8% by weight of uranium enriched to 20% in ^{235}U, for stainless-steel and aluminium clad elements, respectively [4, 5]. The composition of the fuel provides the fuel with an effective moderation property strongly dependent on fuel temperature: the higher the temperature is, the less the neutrons are moderated. Because of this behaviour the fuel temperature coefficient is strongly negative. The core has cylindrical configuration with an annular graphite reflector. There are 91 locations in the core, which can be filled by fuel elements or other components such as control rods, neutron source or measurement channels. The elements are arranged in five concentric rings. The core has 63 fuel elements, composed of 59 original Al-clad fuel elements and 4 fresh SS-clad elements. The power level of the reactor is controlled by three control rods: Regulating, Shim and Safety. The Shim and the Safety control rods are in symmetrical positions of the C-ring, and the Regulating rod is at F-ring. The thermal neutron fluxes in the rotary specimen rack and in the central thimble at 100 kW are 6.4×10^{11} and 4.0×10^{12} cm^{-2}s^{-1}, respectively. Figure 1 shows a view of the reactor, and the geometrical configuration of the fuel elements, the graphite dummy elements and the control rods loaded in the core.

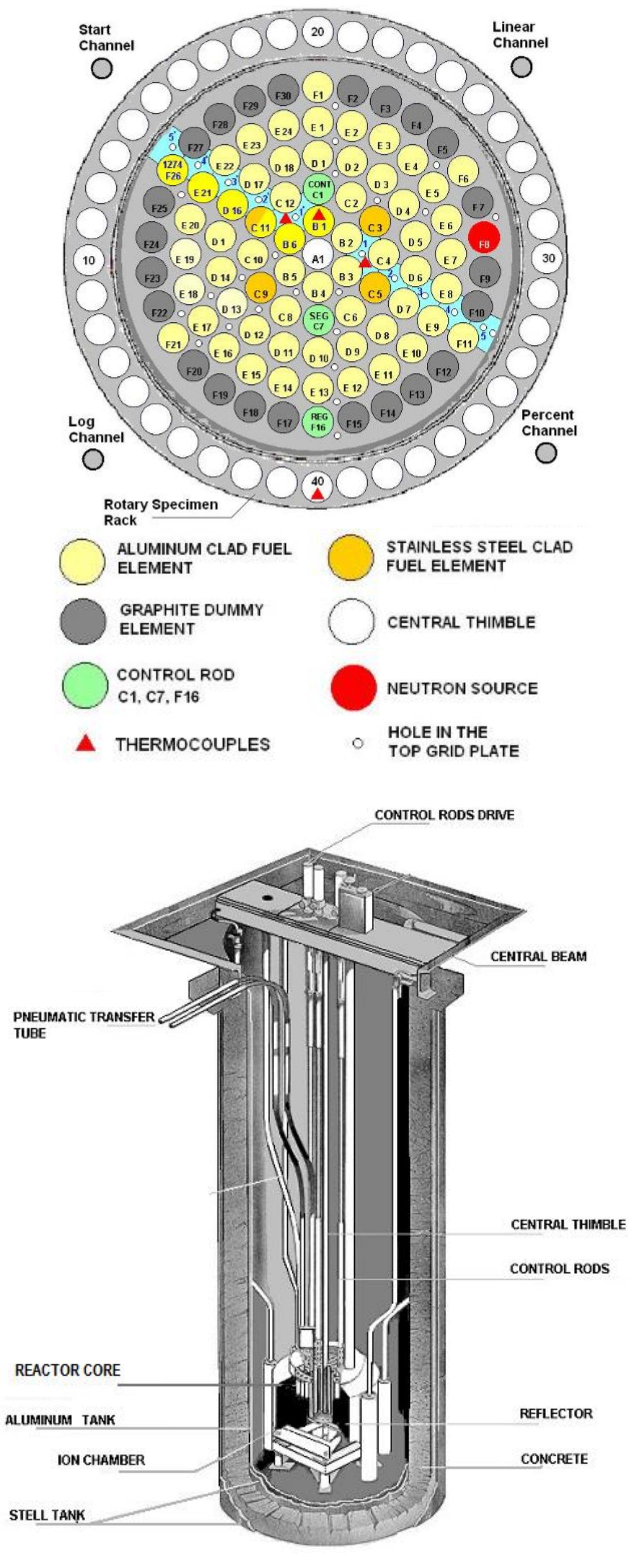

FIG. 1. IPR-R1 TRIGA Mark I nuclear reactor pool.

3. DESCRIPTION OF THE TESTS

3.1 Control rod reactivity worth determination

The knowledge of the reactor’s response to specific control rod motions is essential to the safe and efficient operation of a nuclear reactor. Generally, control rod movements are used to compensate for other reactivity changes resulting from fuel burnup, temperature changes, xenon transients, etc. Control rod calibration enables the determination of the reactivity associated with such changes in the conditions within the reactor.

The control rods were calibrated by the positive period method. The reactor is made critical at 20 W, so that the temperature increase during the experiment was negligible, with the test rod fully inserted in the core. The method consists of withdrawing the control rod from known critical positions through small distances □z. This adds a positive reactivity to the system so that the reactor is slightly supercritical and the power will increase with time. At first, there will be a sharp rate of power increase followed by a more gradual variation, resulting from the production of delayed neutrons, and the establishment of a stable period. After two minutes for the transients to die out, the doubling time, which is the time required for the power to increase by a factor of 2, is determined. Other rod is inserted into the reactor to bring it back to critical. The previous procedure is repeated until the control rod tested has been calibrated along its whole length. The reactor period is determined from the doubling time. The periods measured are used to determine the variation--n of reactivity (□□) inserted by the withdrawal of a control rod, using for this the inhour equation in graphical form. The reactivity change per unit distance (□□□□z) is called the differential rod worth.

Figure 2 shows the differential worth curve of the Regulating control rod, where (□□□□z) values are plotted as function of the rod positions. Note that the worth of the road at the beginning and at the end is small compared to the rod worth in the central portion. This is a general characteristic of control rods and results from the fact that reactivity of a neutron absorber is proportional to the square of the neutron flux. The integral worth curve is obtained by adding up the values of the differential worth. Figure 3 shows the corresponding integral reactivity worth curve of the Regulating rod. The obtained worth of the Regulating control rod was 0.48 $ [6].

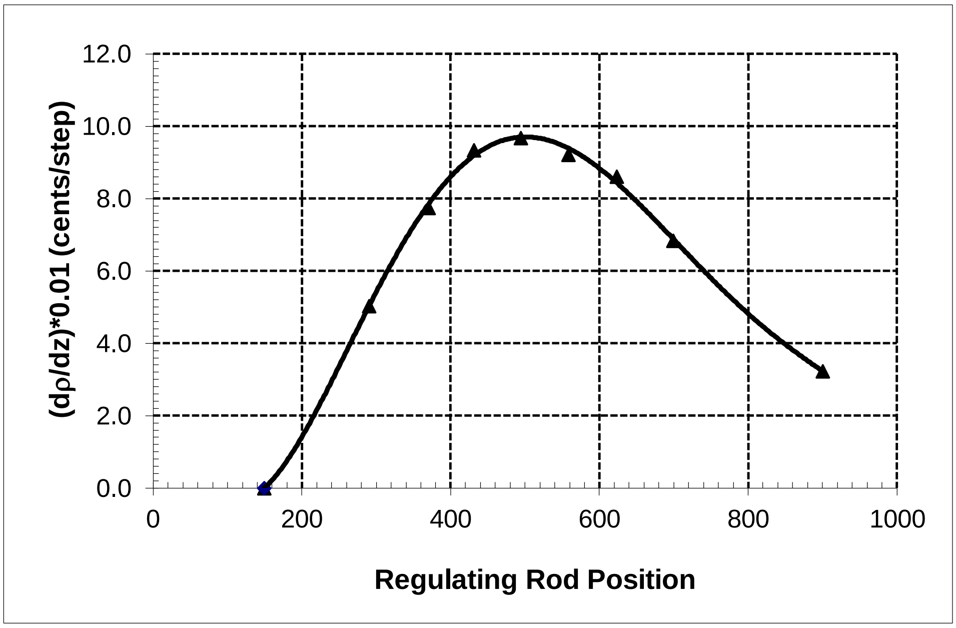

FIG. 2. Differential curve of the Regulating control rod.

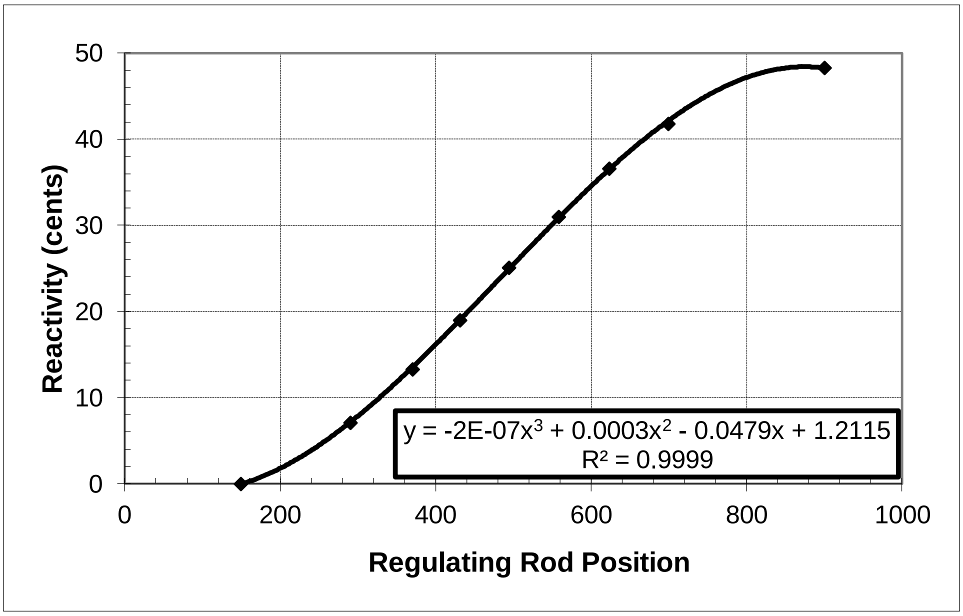

FIG. 3. Integral curve of the regulating control rod.

The Shim and Safety rods were intercalibrated. The basic idea of this method is to measure one control rod in the presence of the other rod, which is used to compensate the reactivity introduced by the step withdrawal of the measured rod. Figures 4 and 5 show the integral calibration curves of the Shim and Safety rods, respectively. Since it is impossible to calibrate the whole Shim and Safety rods, because the total reactivity worth of each control rod exceed the available excess reactivity of the core, their total worth were calculated considering the neutron flux asymmetry, obtained from the Regulating rod calibration curve in Figure 3. Taking the ration between the reactivity at the bottom and at the top of this curve, and considering that the neutron flux has the same shape at the places where the Shim and Safety rods are placed, the total worth of these rods were calculated. The Shim and Safety rods worth were 3.21 $ and 2.84 $, respectively [6]. Both rods have sufficient reactivity worth to shut down the reactor, independently.

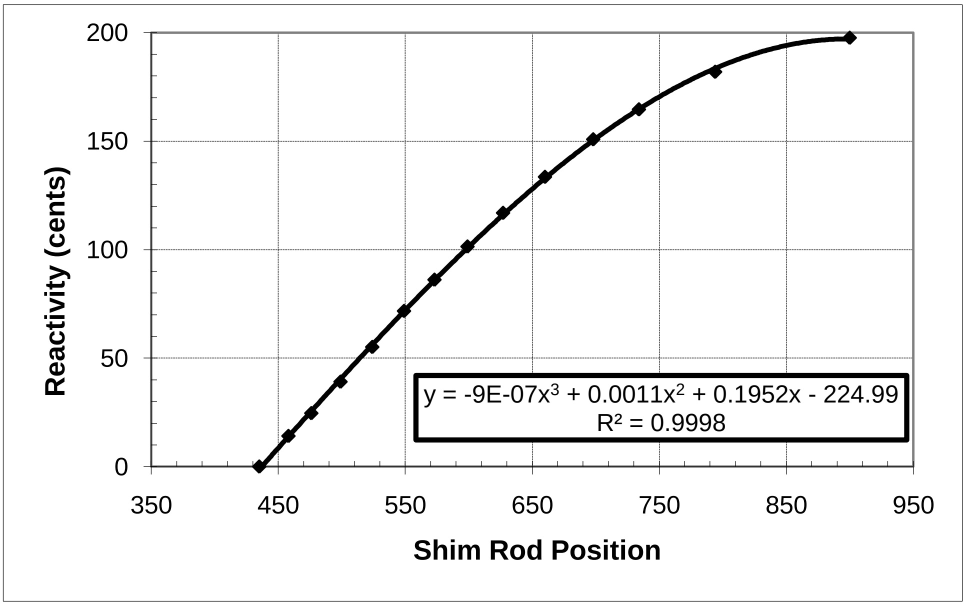

FIG. 4. Integral curve of the Shim control rod.

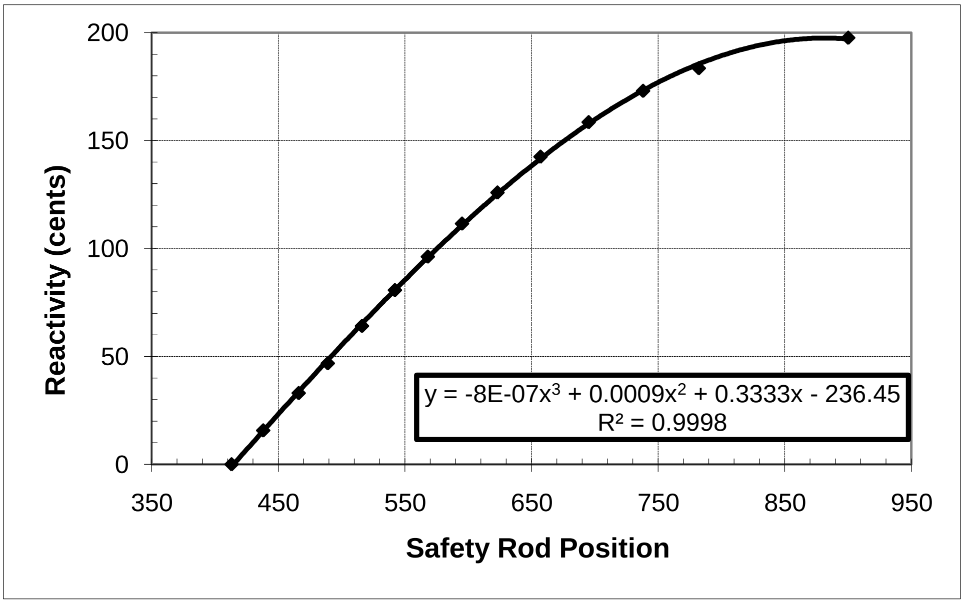

FIG. 5. Integral curve of the Safety control rod.

3.2. Excess of reactivity and shutdown margin measurements

The value of the excess reactivity, ρ_{exc}, must be such as to compensate the effects of negative reactivity feedback due to temperature coefficient, xenon poisoning, void, burning the fuel (long term) and the introduction of samples for irradiation. The excess reactivity is given by the equation [7]:

$$\rho_{exc} = \frac{k_{eff} - 1}{k_{eff}}$$

To measure the excess reactivity (ρ_{exc}) of the core, the reactor was left critical at low power with various configurations of the control rods. The ρ_{exc} values in the Table I were experimentally determined from the reactivity inserted in the core (ρ_{in}) by each control rod, considering the respective calibration curve. Then the average value of the core excess reactivity obtained was (2.00 ± 0.02) $ [6]. The corresponding experimental value of k_{eff} is 1.01605.

TABLE I: EXPERIMENTAL VALUES OF THE REACTIVITY EXCESS FOR SEVERAL CONFIGURATIONS OF CONTROL RODS.

REGULATING ROD		SHIM ROD		SAFETY ROD		ρ_{EXC} (CENTS)	K_{EFF}
POSITION	ρ_{IN} (CENTS)	POSITION	ρ_{IN} (CENTS)	POSITION	ρ_{IN} (CENTS)		
460	26,6	475	173.1	UP	0	199.7	1.01603
531	19.9	UP	0	440	181.6	201.5	1.01618
UP	0	UP	0	416	196.6	196.6	1.01578
UP	0	435	197.6	UP	0	197.6	1.01586
272	42.2	500	158.1	UP	0	200.3	1.01608
391	33.3	486	167.6	UP	0	200.9	1.01613
568	16.2	461	182.6	UP	0	198.8	1.01596

IN	48.3	509	152.1	UP	0	200.4	1.01609
289	41.2	UP	0	469	164.1	205.3	1.01649
472	25.2	475	173.1	UP	0	198.3	1.01592
$\overline{\rho_{exc}} = (2.00 \pm 0.02)\,\$ \quad \Rightarrow \frac{\sigma_\rho}{\rho} = 1.0\,\%$							

The shutdown margin is defined as negative reactivity by which the reactor is subcritical if all control rods were fully inserted in the core except the most reactive rod. The shutdown margin is equal the excess reactivity minus the sum of all control rod worth except the most reactive one. The total reactivity worth of the control system is 6.53 $. With a core excess reactivity of 2.00 $, the shutdown margin with the most reactive rod (Shim) stuck out of the core is 1.32 $ (1043 pcm) [6]. This value of the shutdown margin assures that the reactor can be shutdown from any operating condition with the assumption that the highest worth control rod remains fully withdrawn. The shutdown margin of 1043 pcm satisfies entirely since the minimum safety limit required for TRIGA research reactors is 200 pcm [4, 5].

Table II shows the measured values of the control rods worth, the reactivity excess, and the shutdown margin for the current IPR-R1 reactor core.

TABLE II: RESULTS OF REACTIVITY (β_{EFF} = 0.0079 FOR THE IPR-R1 REACTOR).

	□ ($)	□ □pcm)
Regulating Worth	0.48	379
Shim Worth	3.21	2536
Safety Worth	2.84	2244
Reactivity Excess	2.00	1580
Reactivity of the control system	6.53	5159
Shutdown Margin (Shim rod out)	1.32	1043

3.3. Power defect measurement

When the reactor power increases the temperature of the fuel and the moderator will also increase. Fuel temperature and power are related. The power coefficient (defined as reactivity change per unit reactor power) and the power defect (the integral of power coefficient from zero power to a certain power) are easily measured.

The experiment was performed by increasing the reactor power and, consequently, the fuel temperature by withdrawing the Shim control rod in steps. Initially, the reactor was critical at 20 W and the power was raised in steps of 10 kW. The reactor cooling system was not operating during the measurements. The reactivity was determined from the calibrated curves of the control rods, considering each critical rod position. Figure 6 shows two curves: (□□□□P) and the reactivity loss to achieve a given power level versus the reactor power. A significant amount of reactivity is needed to overcome temperature and allow the reactor to operate at high power. The reactivity needed to operate the IPR-R1 reactor at 100 kW, or the power defect, was 0.76 $ [6]. The curve of the reactivity loss is almost linear, and gives a power coefficient of reactivity about -0.66 ¢/kW.

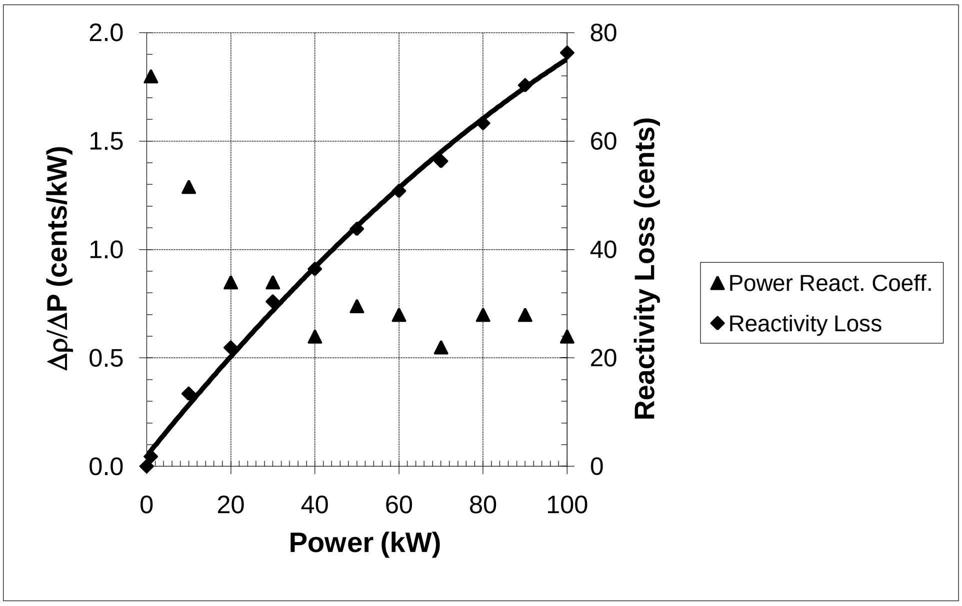

FIG. 6. Reactivity loss and the power coefficient of reactivity versus reactor power.

4. CONCLUSIONS

This paper presents the results of neutronic tests which are performed annually as determined by the RAS of the IPR-R1 TRIGA reactor. The control rods were calibrated by the positive period method and the worth of the Regulating, Shim and Safety rods obtained were 0.48 $, 3.21 $ and 2.84 $, respectively. The excess reactivity obtained for the proposed core, to compensate the effects of negative reactivity feedback, was 2.00 $ (k_{eff} = 1.01605), and the shutdown margin with the most reactive rod stuck out of the core was 1043 pcm, greater than the minimum safety limit (200 pcm) required for TRIGA research reactor. The power defect, or the reactivity required to operate the IPR-R1 reactor at 100 kW was 0.76 $, and the power coefficient of reactivity was -0.66 ¢/kW.

After finishing these tests, several samples were placed in almost all rotary specimen rack positions and they were irradiated for 8 hours at 100 kW, and it was evaluated in 16.2 cents the value of the negative reactivity inserted in the core. The negative reactivities inserted by xenon poisoning, after 8 hours of operation at 100 kW, was 20 cents, and by a void in the central thimble of the reactor was 22 cents [3]. Considering all these negative reactivity values, it is confirmed the need to increase the excess reactivity of the core by adding new fuel elements, in order to operate the reactor at the new power.

ACKNOWLEDGEMENTS

Thanks are due to the the operation staff of the IPR-R1 TRIGA reactor. This research project is supported by Nuclear Technology Development Center (CDTN), Brazilian Nuclear Energy Commission (CNEN), Research Support Foundation of the State of Minas Gerais (FAPEMIG), and Brazilian Council for Scientific and Technological Development (CNPq).

REFERENCES

[1] NUCLEAR TECHNOLOGY DEVELOPMENT CENTRE, “Safety Analysis Report of the IPR-R1 TRIGA Reactor”, CDTN, Belo Horizonte, Brazil (2007), (RASIN/TRIGA-IPR-R1/CDTN). (In Portuguese).

[2] SOUZA, R.M.G.P., RESENDE, M.F.R., “Power Upgrading Tests of the TRIGA IPR-R1

Nuclear Reactor to 250 kW", Second World TRIGA Users Conference, Atominstitute Vienna, Austria, September, 15-18 (2004).

[3] SOUZA, R.M.G.P., MESQUITA, A.Z., "Reactivity Balance in the IPR-R1 TRIGA Reactor", *Progress in Nuclear Energy*, **53** (2011) 307.

[4] GENERAL ATOMIC, "Technical foundation of TRIGA", San Diego, California (1958) (GA-471).

[5] GENERAL ATOMIC, "Safeguards Summary Report for the New York University TRIGA Mark I Reactor", San Diego, California (1970) (GA-9864).

[6] SOUZA, R.M.G.P., "Results of the Calibration of the Control Rods, Reactivity Excess, Shutdown Margin and Power Defect of IPR-R1 TRIGA - Core with 63 F.E.", Belo Horizonte, CDTN (2010) (NI-SERTA-03/10). (In Portuguese).

[7] DUDERSTADT, J.J., HAMILTON, L.J., Nuclear Reactor Analysis, J. Wiley & Sons New York, N.Y. (1976).