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AUTOMATION OF CONTROL ROD REACTIVITY CALIBRATION FOR THE TRIGA IPR-R1 RESEARCH NUCLEAR REACTOR

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ABSTRACT

The TRIGA IPR-R1 reactor is a TRIGA Mark I model, designed and manufactured by General Atomics, USA, and operated by Centro de Desenvolvimento da Tecnologia Nuclear, Comissão Nacional de Energia Nuclear (CDTN/CNEN), Brazil. The main method to manipulate core reactivity of this reactor is through control rods. The reactor has three such control rods, and each control rod has its own reactivity insertion curve, determined by absorption characteristics and position in core, due to non-uniform flux distribution. TRIGA IPR-R1 reactor operators perform annual neutronics tests, including calibration experiments for the control rods. Traditionally, data acquisition from the reactor is manual, which is less than optimal considering the technologies and resources currently available. Therefore, a modern data acquisition computer system is being developed, opening up several possibilities for research in reactor physics and, among them, enabling more precise calculation methodologies for control rod calibration. The use of this computer system is limited to data acquisition: due to safety concerns, it is not allowed to actuate on the control bars. Therefore, in this work we propose a new control rod calibration methodology for automating, as far as possible, the procedure using the data acquisition system. The results show that the new methodology generates results comparable to previous years. Furthermore, it is not necessary to return the reactor to criticality at each step, reducing the experiment time. And all human influences on the uncertainty of the results were removed.

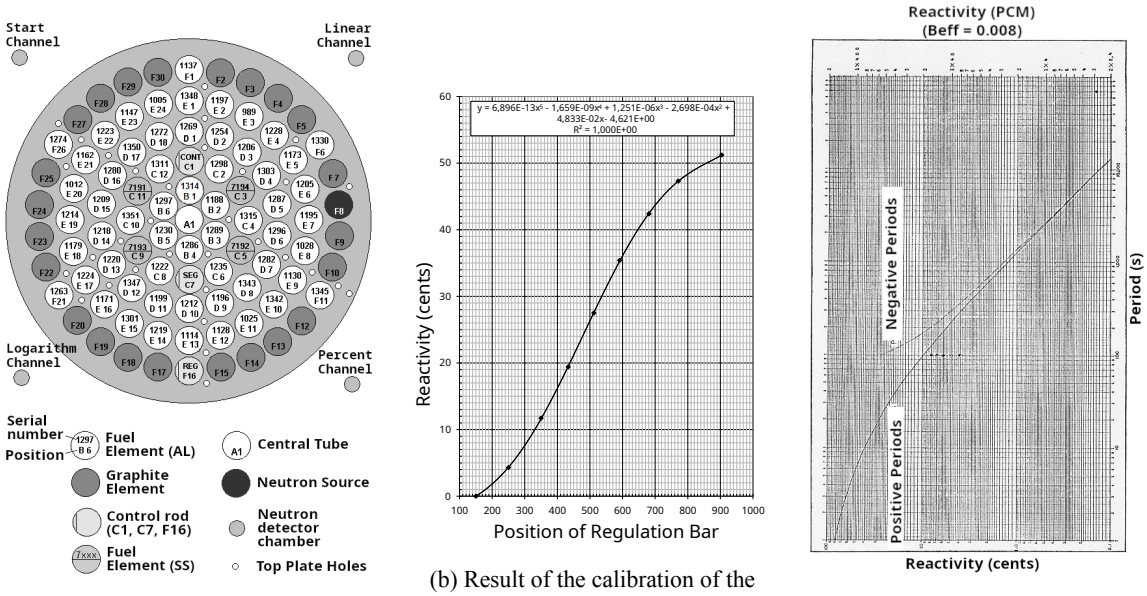
1. INTRODUCTION

TRIGA nuclear research reactors, designed by General Atomics, were intended for educational, research, and isotope production purposes [1]. The TRIGA IPR-R1 reactor, a Mark I model, was inaugurated in 1960 at Instituto de Pesquisas Radioativas, Universidade Federal de Minas Gerais (IPR/UFMG), nowadays Centro de Desenvolvimento da Tecnologia Nuclear, Comissão Nacional de Energia Nuclear (CDTN/CNEN), Brazil [2].

In TRIGA reactors such as the IPR-R1, the primary way to control reactivity is by changing the position of control rods. In the case of the TRIGA IPR-R1 reactor, there are three absorber rods identical in their material composition and geometric design, their positions and names can be seen at Fig. 1a, as the rest of core.

The “Safety” and “Shim” rods are in radially symmetrical positions with respect to the core’s center, so that they should have similar reactivity influence, minus local flux asymmetries. On the other hand, the “Regulation” rod’s radial position within the core is different, farther from the center, so that it is exposed to a lower neutron flux and, consequently, has a lesser influence on the reactor’s overall reactivity.

Each rod's influence in reactivity depends also on its respective axial position (insertion). Due to the neutron flux reactor core's nonlinearity, the same change in axial position, for the same rod, can alter reactivity in different values depending on its initial position. In general, when rod is nearer to its uppermost or lowermost positions, big changes in position do not have much impact on reactivity due to those being low flux regions. Following the same reasoning, small changes in position do have a big impact on reactivity when the rod is on its middle position, nearer to the core center, due to that being a maximal flux region.
A control rod calibration procedure is used to quantify the reactivity influence at each rod position. The results of such procedure allow the operator to determine how much of the bar must be inserted or removed in order to achieve a given amount of reactivity change. They can also be used to subsidize other neutronic tests such as temperature defect, reactivity excess, etc. An example of a calibration curve can be seen in Fig. 1b, and the relationship between reactivity and reactor period used to determine that calibration curve, the InHour curve, is given by Fig. 1c.



(a) Core setup in October/2023.

(b) Result of the calibration of the regulation bar in October/2023.

(c) Official IPR-R1 InHour Curve.

Figure 1. TRIGA IPR-R1 reactor data (translated from Prado Souza [2]).

Every year CDTN repeats the experimental procedures to obtain new calibration curves for all three control rods. Such experiments have traditionally been performed using a manual methodology. The availability of a new data acquisition system opened up the possibility of automating that experimental process.
Thus, the aim of this study is to create a method for automating the calibration process while taking into account the current system's limitations, which do not permit direct rod position control. The goal of this approach is to improve the calibration process's efficiency and precision by, as far as possible, turning manual measurements and calculations into computational measurements and calculations, while also eliminating the need of operator making the reactor critical for each new measurement.

2. METHODOLOGY

CDTN uses an educational approach to annually calibrate IPR-R1 control rods, the same used in CTORP (Research Reactor Operator Training Course) classes, with the aim of retraining reactor operators. However, in this methodology, time measurements are made manually using human-operated stopwatches; the conversion of period of reactivity is done manually by looking up in a printed Inhour graph with the aid of a ruler; and all calculations are done manually, at most with the aid of a pocket calculator. All those manual measurements may obviously increase the uncertainty of the result.
According to Prado Souza [2], calibrate the "Regulating" rod by the "Positive Period Method" involves the following procedure:

- Set the reactor to critical ($\rho_{initial} = 0$) at 2.5W with the "Safety" rod in it is upper position and the "Regulating" rod in it is lower position;
- Withdraw the "Regulating" rod by a determined amount (Δx_i);
- Wait $90\,\mathrm{s}$;
- Measure the period by the "doubling time" (t_d) of reactor power;
- Return the reactor to critical at $2.5\,\mathrm{W}$ by adjusting only the "Control" rod;
- Repeat the previous steps until the "Regulating" rod reaches its upper limit.

Several doubling time measurements are performed in order to obtain an average value, reducing uncertainties. Afterwards, doubling time is converted to period (T) by $T = \frac{t_d}{\ln 2}$. Then, all the period measurements are converted to reactivity (ρ_{final}) using the InHour curve in Fig. 1c, printed on millimeter graph paper. Calculations assume that the control rod is removed from the reactor during a critical state [3], resulting in the theoretical delta reactivity value, because $\Delta\rho_i = \rho_{final} - \rho_{initial} = \rho_{final} - 0$. The calibration curve, which represents reactivity (ρ) in function of rod withdraw (x), using the formula $\rho(x_i) = \rho(x_{i-1}) + \Delta\rho_i$, and considering that $\rho(0) = 0$. Here, the official results were generated by a computer using the same manual collected data, as in Fig. 1b.

2.1. Proposed methodology: Differential Reactivity

The current method assumes the reactor is at zero reactivity. If the reactor is near criticality but not exactly critical, this could result in an error in the calculation of $\Delta\rho$. To overcome this measurement uncertainty, it is proposed to initiate rod withdrawal from a reactivity other than zero, measuring reactivity before and after the withdrawal, to effectively calculate $\Delta\rho$.
As a way to reduce the measurement uncertainties of reactivities, as well as rod positions, we use the reactor's data acquisition system currently in development, collecting rod position over time ($r(t)$) and reactor power over time ($P(t)$), and subsequently processing these signals. Although this automation does not control the rods, which will be controlled by the operator, regardless of the amount of such manual withdrawal, the system will be able to accurately calculate Δr and $\Delta\rho$, meaning the measurement uncertainty will not depend on human skill, but on the signal resolution and signal-to-noise ratio.

2.1.1. Separation of Time Windows

Since the proposed methodology assumes that the initial reactivity will be different from 0, this allows successive rod withdraw (Δr), as long as reactivity and power are below the allowed values, in addition to the power being below the minimum value to generate a significant temperature effect.

This procedure must be performed with data acquisition turned on all time, before, during and after the various steps. Then the saved temporal data can be processed to calculate the calibration.
It can be defined key times t_N based in rod withdrawal (step) in same data acquisition as: t_0 as start of data collection (0 s); t_1 as $t_0 + t_a$; t_2 as start of control rod movement; t_3 as end of control rod movement; t_4 as $t_3 + t_a$; t_5 as start of a new control rod movement; and so on.
t_a stands for "accommodation time" and indicates the time necessary to delay neutrons dynamic create a stable period after a reactivity change. According to the previous methodology, it was determined as 90 s [2]. By the derivation of the rod's position ($\dot{r}(t)$), it can be determined by the times t_2 and t_3. Where t_2 is can be set when the derivative value goes beyond a predetermined threshold, and t_3 when goes back to below of it.
So the signal of rod position and reactor power can be separate in time windows, defined by the time interval between key times:

- Window 1 (t_0 to t_1): Initial time for delayed neutron accommodation.
- Window 2 (t_1 to t_2): Initial stable period.
- Window 3 (t_2 to t_3): Control rod in motion (changing in reactivity).
- Window 4 (t_3 to t_4): New time for delayed neutron accommodation.
- Window 5 (t_4 to t_5): New stable period.

The use of only stable periods for calculations is the reason why data from windows 1, 3, and 4 can be discarded.

2.1.2. Calculation of variation of reactivity and rod position

Time windows 2 have the signal of rod position ($r_2(t)$) in a constant value and the reactor power signal ($P_2(t)$) changing with a stable period before the rod withdrawal, while windows 5 have the same kind of signal after the rod withdrawal ($r_5(t)$ and $P_2(t)$).
The delta position of the control rod (Δr) can be calculated using the mean value of $r_5(t)$ (r_5) and the mean value of $r_2(t)$ (r_2), that is, $\Delta r = r_5 - r_2$. Even though the position of the control rod in these windows are constant, the position value can be influenced by noise that comes from different sources (electrical, electromagnetic, etc), so taking the average value of this uncertainty may decrease if the noise has a mean value of zero.
About reactivity calculation, the doubling time could be used in each power signal ($P_2(t)$ and $P_5(t)$), however, it considers only two points for calculation in a signal that may also have noise and other measurement uncertainties. Additionally, the lower the reactivity, the longer will be the waiting time to perform the test, because it will take more time for power double itself [4].
To increase the number of points used for the calculation, in order to reduce uncertainty and decrease the time required to conduct the test, exponential regression in the form $f(x) = a \cdot e^{bx}$ has applied in power signal from neutron detectors. According to Duderstadt and Hamilton [5], the period and temporal evolution of neutron population are given by

$$T = \frac{l}{k-1}; N(t) = N_0 \cdot e^{\frac{k-1}{l}t}, \tag{2.1}$$

Where T is period, l is neutron life-time, k is multiplication factor, N is current neutron population, N_0 is initial neutron population and t is time. Making $x = t$ and $f(x) = N(t)$, we have

$$a \cdot e^{bt} = N_0 \cdot e^{\frac{t}{T}} \implies N_0 = a; T = \frac{1}{b}, \tag{2.2}$$

so the period is determinate by raising the value of exponent found in exponential regression to -1. The period value found for each window (T_2 and T_5) can be converted to respective reactivity in each window (ρ_2 and ρ_5) using the InHour equation. Unfortunately, CDTN does not provide a official InHour equation for IPR-R1 reactor, only a official graph of InHour curve. According to Matthias Baron and O'Kelly [1], a InHour equation for 6 delay neutrons is give by

$$\rho(T) = \frac{l}{T} + \sum_{i=1}^{6} \frac{\beta_i}{1 + \lambda_i \cdot T}, \tag{2.3}$$

witch coefficients for a generic TRIGA reactor are

$$l = 0.000073; \beta_{eff} = 0.007; \beta_1 = 0.00021; \beta_2 = 0.00141; \beta_3 = 0.00127; \tag{2.4}$$
$$\beta_4 = 0.00255; \beta_5 = 0.00074; \beta_6 = 0.00027; \lambda_1 = 0.01243982736; \lambda_2 = 0.03050823858;$$
$$\lambda_3 = 0.1114384535; \lambda_4 = 0.3013683394; \lambda_5 = 1.136306853; \lambda_6 = 3.013683394.$$

The calibration curves generated by different InHour curves may differ from those obtained by the current methodology in the reactor [6]. The equation is the preferred choice over the graph because it makes it possible to calculate the reactivity value computationally without the uncertainty of manual measurements. Then it is necessary to generate an InHour equation that corresponds to the official InHour curve of the IPR-R1 reactor, seen in Fig. 1c.
The official IPR-R1 InHour graph was reproduced in Fig. 2, together with the curve generated by the IAEA equation. A 25 % heuristic adjustment in the InHour equation provided by the IAEA was enough to generate a curve similar to the official IPR-R1 curve, as also can be seen in Fig. 2.

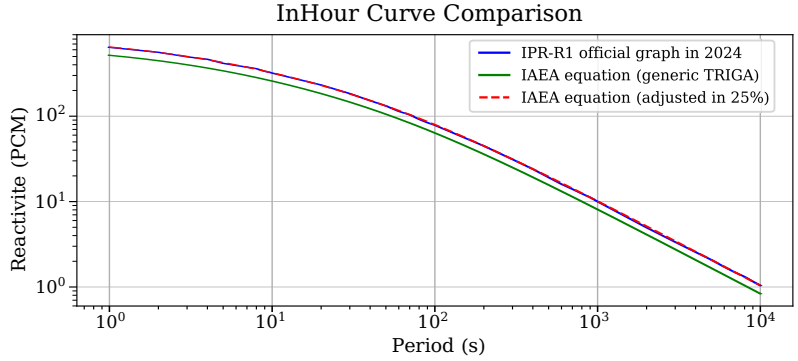
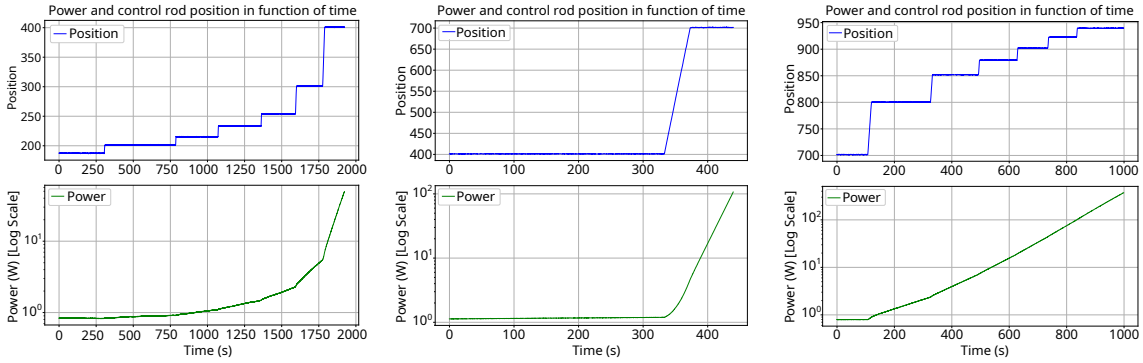


Figure 2. Comparison of official IPR-R1 InHour graph with InHour equations

The adjusted InHour equation was used in the computational calculations of this work, in order to generate results comparable to previous years. However, it is necessary to generate an official InHour equation for the IPR-R1 reactor, which corresponds to the current fuel composition, considering that the current official curve corresponds to the fresh fuel.

3. RESULTS

The control rod calibration experiment was conducted on the regulation rod (position F16 of the core), where three data acquisitions composed by many steps were performed, as shown in Fig. 3. Those steps swept the entire course of the "regulating" rod.



(a) Sweep rod position from 187 (DOWN) to 400.

(b) Sweep rod position from 400 to 700.

(c) Sweep rod position from 700 to 940 (UP).

Figure 3. Regulating rod calibration experiment carried out for this work.

A Python code has been created that can read files that contain reactor temporal data and apply the new methodology. The code automatically cuts time windows based on the regulation rod's movement, as can be seen in Fig. 4, which represents the 5th step shown in Fig. 3a. In Fig. 4 can be seen the exponential regression in windows 2 and 5, with the corresponding exponent values (b_2 and b_5) as listed at line 5 of Tab. 1. The exponential regression curve for window 5 is extended from window 3 in order to emphasize the significance of accommodation time: The real curve in window 4 differ from extended exponential regression of window 5, due to the unstable period. All results for each step are concatenated in Tab. 1.

*i	r_2	r_5	Δr	b_2	b_5	T_2	T_5	ρ_2	ρ_5	$\Delta\rho$
1	187.15	201.42	**14.27**	-8.10E-05	1.62E-04	-12341	6161.5	-0.85	1.69	**2.54**
2	201.42	215.29	**13.87**	1.62E-04	6.27E-04	6161.5	1595.51	1.69	6.41	**4.72**
3	215.29	233.29	**18.01**	6.27E-04	9.75E-04	1595.51	1025.68	6.41	9.86	**3.44**
4	233.29	254.08	**20.79**	9.75E-04	1.78E-03	1025.68	560.28	9.86	17.59	**7.72**
5	254.08	301.22	**47.14**	1.78E-03	4.28E-03	560.28	233.44	17.58	39.2	**21.6**
6	301.22	400.74	**99.52**	4.28E-03	1.41E-02	233.44	71.06	39.2	103	**63.8**
7	401.27	701.46	**300.19**	1.67E-04	4.67E-02	5991.63	21.41	1.72	221.61	**219.87**
8	701.58	800.44	**98.86**	2.61E-05	4.52E-03	38371	221.44	0.26	41.05	**40.79**
9	800.44	851.95	**51.5**	4.52E-03	6.38E-03	221.44	156.66	41.05	55.25	**14.19**
10	851.95	879.43	**27.48**	6.38E-03	7.18E-03	156.66	139.32	55.25	60.91	**5.66**
11	879.43	902.03	**22.61**	7.18E-03	7.70E-03	139.32	129.92	60.91	64.51	**3.59**
12	902.03	922.79	**20.76**	7.70E-03	8.04E-03	129.92	124.44	64.51	66.81	**2.3**
13	922.79	939.48	**16.7**	8.04E-03	7.87E-03	124.44	127.09	66.81	65.67	**-1.12**

Table 1. Data extracted from windows 2 and 5, referring to all steps.
*i is the step number; r is the rod position (dimensionless); b is the exponential coefficient (s^{-1}); T is the period (s); ρ is the reactivity (PCM).

Based on the values of Δr and $\Delta\rho$ for each step from Tab. 1, a rod calibration graph can be constructed, generating Fig. 5. The total reactivity of the rod found (sum of all $\Delta\rho$) is 389.1 PCM.

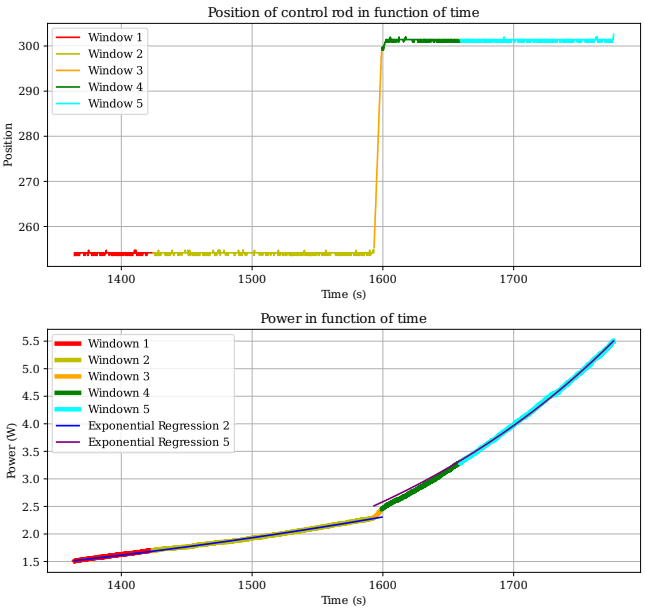


Figure 4. Time windows for the 5th step

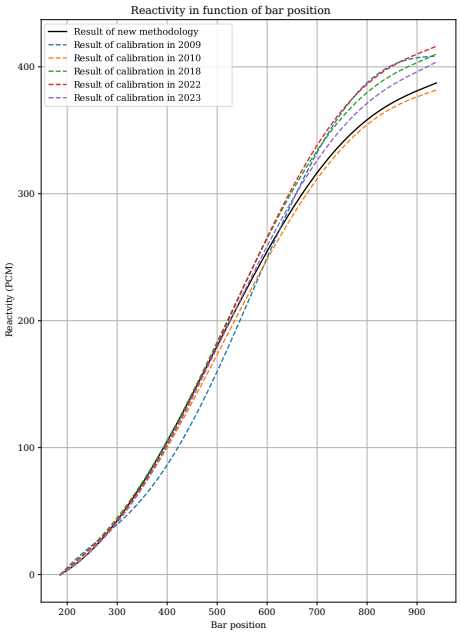


Figure 5. Final Result

To verify the consistency of the result, a comparison with results from previous years, provided by CDTN (2009, 2010, 2018, 2022, and 2023), shows that the total rod reactivity found in each of these years is 409.2 [7], 381.6 [8], 410.1 [9], 416.3 [10], and 404.1 PCM [2], with an average of 404.26 PCM. After translating these curves in order to account for different ranges of the regulation rod, as contrasted to the current one (minimum position 187, maximum position 940), they can also be seen in Fig. 5. It is possible to conclude that the curve generated by this work is in the middle of the maximum and minimum curves from previous years.

4. CONCLUSION

This work presents an improved methodology and procedure for calibrating nuclear reactor control rods. This approach is designed to address the problems with the current methodology, which requires the reactor to return to criticality after each control rod movement. The current experimental procedures take a long time and uncertainties may be introduced due to manual measurements and other human factors. The new, proposed methodology uses a computational data acquisition system and computer calculations to achieve more precise reactivity calculations and reduce uncertainty and test time requirements. Furthermore, it permits a series of steps, avoiding the need to return the reactor to criticality after each reactivity insertion. By using the methodology, the calibration process can be optimized, maintaining operational safety, and improving the accuracy of the results obtained.

To perform calculations computationally, a generic InHour equation for TRIGA reactors was used, adjusted to correspond to the official InHour graph of the IPR-R1. This work's results demonstrate that the new methodology can produce results that are comparable to those generated by the current methodology. Additionally, there is no need to bring the reactor to criticality at every stage,

which significantly reduces the overall experiment duration. Moreover, all uncertainties related to human influence were eliminated, as neither the measurements nor the calculations are performed manually, and calculations are independent of the operator's ability to adjust the reactor's reactivity close to zero.
The next step is to assess the uncertainty of both methodologies, to investigate the position influence of "Shim" rod on calibration curve of "regulating" rod, and to develop a new InHour equation for the reactor that matches the current fuel composition. The analysis of the uncertainty of this new InHour equation is crucial for understanding the propagation of uncertainty in control rod calibration.

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