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Original Article

Evaluation of the Fuchs-Nordheim model including heat capacity variation for a TRIGA® reactor

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Abstract: The TRIGA® (Training, Research, Isotope General Atomics) are reactors that, currently, are utilized for staff training, radioisotope production and for researching in many areas of science; nowadays, more than 20 countries own TRIGAs®, including Brazil. These reactors have two operating modes: steady state (where it operates within constant neutron flux and its parameters also remain constant) and pulsed mode, in which a single control rod (named transient rod) is quickly withdrawn from the core, increasing reactivity and leading to a prompt supercritical state, which causes an exponential increase in power and temperature. However, due to the negative temperature coefficient of reactivity of the fuel used to feed the reactor, the power reaches a peak, and it rapidly decreases until shutting down fission reactions, in a process that is inherently safe. The pulses that are generated during reactor operations can have its parameters described by mathematical models, such as Fuchs-Nordheim modelling, that equate the behavior of reactivity, power and temperature during the lifespan of the pulse. However, the current model has some basic limitations, mainly because it considers that parameters such as heat capacity remain constant during the whole process, and it is known that, in practical cases of nuclear reactor operations, heat capacity is a parameter that is a function of temperature. Therefore, this article aims to evaluate the impact that the introduction of heat capacity as a linear function of temperature has on final results, comparing data with and without this assumption.

Keywords: Heat Capacity; Fuchs-Nordheim; TRIGA® Mark II Research Reactor; Improved Pulse Model; Pulse

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Avaliação do modelo de Fuchs-Nordheim incluindo a variação da capacidade calorífica para um reator TRIGA®

Resumo: Os TRIGA® (*Training, Research, Isotope General Atomics*) são reatores que, atualmente, são utilizados para treinamento de pessoal, produção de radioisótopos e para pesquisa em diversas áreas da ciência; nos dias atuais, mais de 20 países possuem TRIGAs®, incluindo o Brasil. Tais reatores possuem dois modos de operação: estado estacionário (no qual ele opera em um fluxo constante de nêutrons e os seus parâmetros também permanecem constantes) e o modo pulsado, em que, durante a remoção de uma única barra de controle (denominada transiente) há um aumento na reatividade e, com isso, induz-se um estado de super pronto-criticalidade, o que ocasiona em um aumento exponencial na potência e temperatura. Porém, devido ao coeficiente negativo de temperatura do combustível utilizado para alimentar o reator, a potência alcança um pico e rapidamente diminui até o encerramento das reações de fissão, em um processo que é inerentemente seguro. Os pulsos que são gerados durante a sua operação podem ter seus parâmetros descritos por modelos matemáticos, tais como o modelo de Fuchs-Nordheim, que equaciona o comportamento da reatividade, potência e temperatura durante o tempo de vida do pulso. Contudo, o modelo atual possui algumas limitações básicas, principalmente por considerar que parâmetros como a capacidade calorífica permanecem constantes durante todo o processo e, em casos práticos de operação de reatores nucleares, a capacidade calorífica é uma função da temperatura. Portanto, este artigo busca avaliar o impacto que a introdução da capacidade calorífica como função linear da temperatura exerce nos resultados finais, comparando os dados com e sem essa modificação.

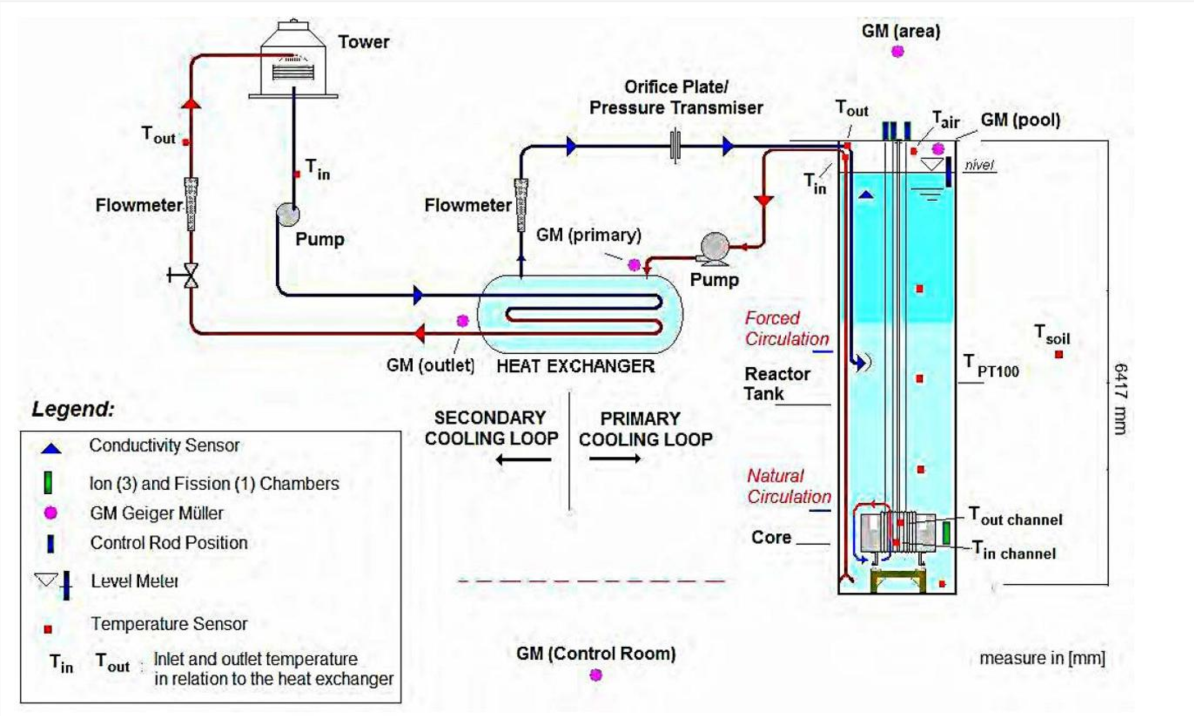
Palavras-chave: Capacidade Calorífica; Fuchs-Nordheim, Reator de Pesquisa TRIGA® Mark II; Modelo de Pulso Modificado; Pulso

1. INTRODUCTION

With its concept idealized in the 20th century, during a United Nations conference and aiming to use nuclear energy for peaceful purposes, the TRIGA® (Training, Research, Isotope General Atomic) are a class of reactors that had its first projects developed in 1956 by General Atomics, that initially composed a group made by veterans of Project Manhattan, that sought ways to commercialize nuclear reactors. The first designs could reach a maximum of 10 kW of power and had its core cooled by freon cooling coils. Lately, more modern designs could reach 250kW and, in 1959, it was possible to reach up to 1,5 GW, returning safely to 500 kW without any kind of human intervention. Nowadays, these reactors can be operated on steady state, where it works within a constant power level such as any other kind of reactor, and can also operate in a pulsed state. [1]

Nowadays, TRIGAs® have many purposes, such as iodine irradiation for applications in the health sector, radioisotope production for the industry, tracers for environmental studies and even for analyzing mineral samples in large scale. Today, these reactors are owned by 24 countries, being present in many universities (including Brazil with the IPR-R1 reactor, described in Figure 1 below), governmental institutions, laboratories and even medical centers. [1-5]

Figure 1: IPR-R1 TRIGA® reactor cooling system



Source: [6]

In pulsed state, with the reactor in a subcritical state and the normal control rods inserted in the core (typically three in TRIGA®s up to 250 kW), a single rod named transient rod is inserted into the core. The normal control rods are then withdrawn from the core, leaving only the transient rod, which has negative reactivity to keep the reactor subcritical. This rod is then rapidly withdrawn from the core, producing a power pulse (on the order of a few megawatts in a few milliseconds). [7]

Within the power pulse (and insertion of reactivity), temperature increases exponentially and the system reaches a state of prompt supercriticality, where the reactor becomes critical with only prompt neutrons, discarding any contribution of delayed neutrons. Normally, this condition would be dangerous for a nuclear reaction; however, due to the negative temperature coefficient of reactivity in the fuel used to feed the reactor, the power peak increases the fuel-moderator temperature and, consequently, it causes a negative reactivity that reduces the power again and leads to a self-shutdown. The fuel is an alloy made of zirconium hydride and uranium (U-ZrH) that is enriched at 20% in ^{235}U. [7-12]

The generated pulses during reactor operations can have its parameters, such as power, reactivity and temperature modelled by mathematical equations, such as Fuchs-Nordheim model. Fuchs-Nordheim modelling was initially created by the physicians Klaus Fuchs and Lothar Wolfgang Nordheim, and is mainly used to represent the behavior of the transient generated by the pulse during its short lifetime, allowing to make qualitative analysis in its parameters. [13]

However, the proposed model has some practical limitations. That occurs mainly because it was considered that variables such as heat capacity remain constant during the power peak, which does not occur in a real case of nuclear reactor operation and limits possible quantitative analysis because this factor is altered with the variation of temperature. [13, 14]

1.1. Objectives and Expected Results

To solve the problem presented by the initial simplification of Fuchs-Nordheim, it is necessary to introduce modifications in the basic premises that the first equations assume, aiming to guarantee more reliability to the final results that are obtained by Fuchs-Nordheim modelling. Moreover, when seeking to validate the modified model, it is essential to compare the mathematical results with data that were acquired by practical means.

Therefore, this article aims to introduce a modification in previous Fuchs-Nordheim model, seeking to create new equations that can be applied in real examples, by introducing heat capacity as a linear function of temperature and comparing the result with practical data obtained by a TRIGA® reactor.

2. MATERIALS AND METHODS

2.1. Standard Fuchs-Nordheim

The standard model starts off from the basic reactor differential ordinary equations (ODEs) for point kinetics equations, in which power can be stated as Equation 1: [15-17]

$$\frac{dP}{dt} = \frac{\rho-\beta}{\Lambda}P(t) + \lambda C \tag{1}$$

where "P" is power, "t" time, "ρ" reactivity, "β" represents delayed neutron fraction, "λC" the delayed neutron contribution and "Λ" the mean neutron generation time. The equations also describe the behavior of reactivity, seen by Equation 2: [15-17]

$$\rho(t) = \rho_o - \alpha T \tag{2}$$

where "ρ_o" represents initial reactivity, "α" the temperature reactivity coefficient of the fuel and "T", temperature [16]. This equation can also be differentiated, generating Equation 3:

$$\frac{d\rho}{dt} = -\alpha\frac{dT}{dt} \tag{3}$$

Temperature can also be equated in an ODE, described by Equation 4:

$$\frac{dT}{dt} = KP \tag{4}$$

where "K" is the reciprocal of heat capacity, "C", as stated in Equation 5:

$$K = \frac{1}{C} \tag{5}$$

Lastly, substituting Equation 4 in Equation 3, the result is given by Equation 6:

$$\frac{d\rho}{dt} = -\alpha KP \tag{6}$$

With these equations, the standard Fuchs-Nordheim model was obtained by solving the ODEs given in Equation 1, 4 and 6, seeking to obtain the behavior of power, reactivity and temperature, utilizing analytical methods such as separation of variables and integration of factors.

When solving each of the ODE's, it is possible to obtain Equations 8, 9 and 10, which describe reactivity, power and temperature during time.

$$\rho(t) = \beta - (\rho_o - \beta)\tanh\left[\frac{(\rho_o - \beta)t}{2\Lambda}\right] \quad (8)$$

$$P(t) = \frac{(\rho_o - \beta)^2}{2\alpha K\Lambda} sech\left[\frac{(\rho_o - \beta)t}{2\Lambda}\right] \quad (9)$$

$$T(t) = \frac{\rho_o - \beta}{\alpha} tanh\left[\frac{(\rho_o - \beta)t}{2\Lambda}\right] \quad (10)$$

while the maximum power that can obtained, P_{max}, is described by Equation 11:

$$P_{max} = \frac{(\rho_o - \beta)^2}{2\alpha K\Lambda} \quad (11)$$

The analytical results can also be represented graphically. Table 1 shows the values for each constant used in every equation in the previous results, utilizing the meter-kilogram-second (MKS) unit system for the modelling.

Table 1: Constants used to obtain the graphical pulse behavior

Constant used	Values
α	$10^{-4}\ pcm/°C$
β	0.007
ρ_o	$3\beta = 0.021$
C	341.6 J/kg ∗ K
Λ	$10^{-4}\ s$

Source: [15]

For solution, additional premises were taken into consideration, aiming to keep the results as precise as possible to reality:

- The whole system is adiabatic, which means that there is no heat exchange with external means and the liberated energy goes to the fuel. This occurs mainly because the pulse is generated and eliminated in fractions of second, and the window to occur heat transfer is too short; [15]
- The contribution of delayed neutrons "λC" is not considered, since the reactor is in prompt supercritical state, becoming critical with only prompt neutrons; [15]
- The reactor initiates pulse formation with an initial power P = 0, mainly because it is initially subcritical or with a negligible initial power; [15]
- The changes in reactivity occur instantaneously, because, with the withdrawal of the control rods, the generated transient occurs in milliseconds. [15]

2.2. Modified Fuchs-Nordheim

For obtaining the modified Fuchs-Nordheim equations, assuming that heat capacity, "C", varies linearly with temperature, it was considered that C varies according to Equation 7: [18]

$$C = \mathrm{a} + \mathrm{bT} \tag{7}$$

where "a" and "b" are arbitrary constants of the introduced modification. The final results obtained by the standard and modified Fuchs-Nordheim equations were compared with the JSI TRIGA® Mark II, a reactor owned by Jožef Stefan Institute, in Slovenia, utilizing the same constants. [15]

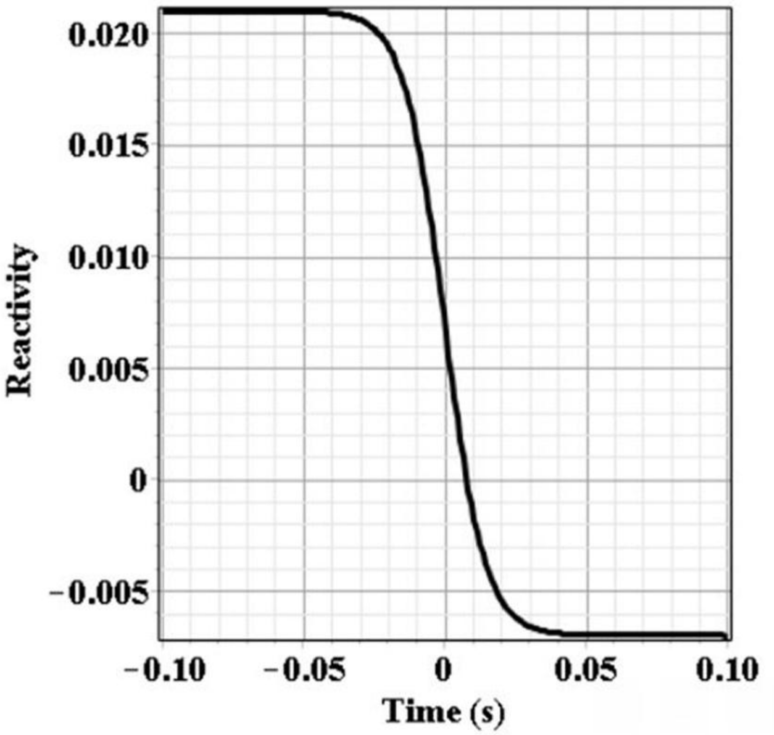
The IPR-R1 TRIGA® reactor in Belo Horizonte, being one of the first TRIGA®-type reactors (first criticality in 1960) was not selected to comparison because it does not have automatic start-up, only manual start-up. It also lacks a system for removing the transition rod to produce a power pulse. Even if it were adapted for pulsed power, all 58 of its fuel elements, whose claddings are made of aluminum, would have to be replaced, as they would not withstand the high temperature caused by the pulse. The IPR-R1 has only four fuel elements with stainless steel cladding. [7]

3. RESULTS AND DISCUSSIONS

3.1. Standard Fuchs-Nordheim

Applying the standard Fuchs-Nordheim formulations yielded the following results for the behavior of reactivity, power, and temperature as a function of time for the JSI TRIGA® Mark II.

Figure 2: Behavior of reactivity as a function of time

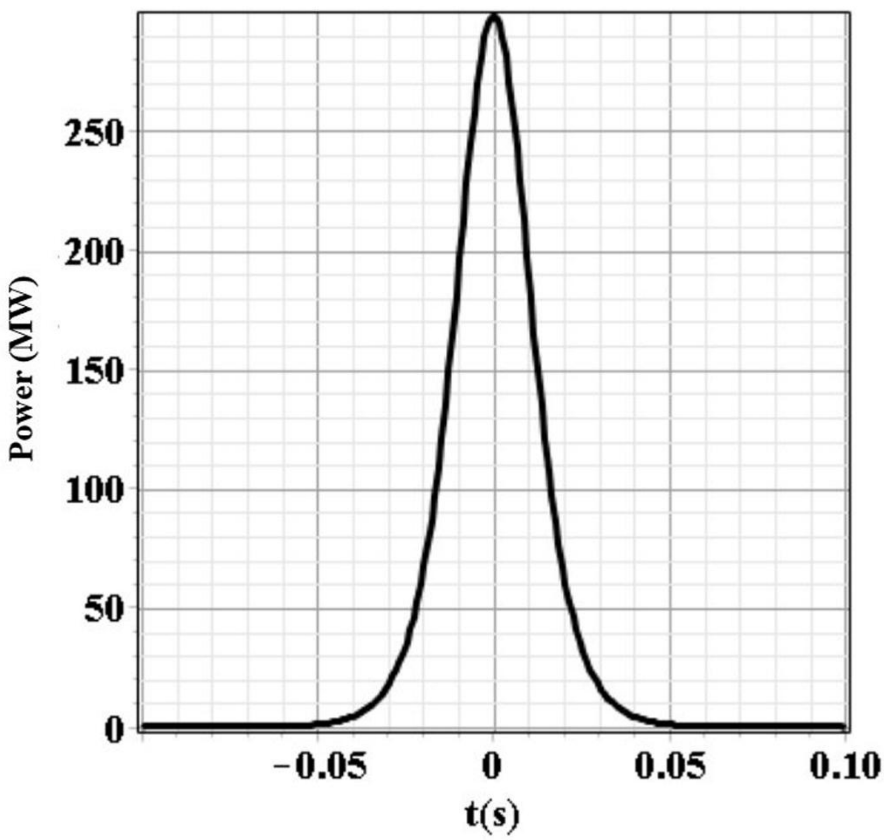


Source: Author

The reactivity remains constant at approximately 0.021, which corresponds to the reactivity inserted by the pulse rod withdrawal prior to the prompt chain reaction. At around t = -0.05 s, the reactivity begins to decrease sharply, due to the negative fuel temperature coefficient inherent to TRIGA® reactors, and with the rising power, the zirconium hydride fuel temperature increases rapidly, introducing negative reactivity that counteracts the initial inserted value.

After that, when t ≈ 0.01 s, the reactivity crosses zero, which corresponds to the instant of peak power. Beyond this point, the reactor becomes prompt subcritical, and the reactivity stabilizes at approximately -0.007 (~-$1). This residual negative reactivity is responsible for suppressing the pulse and shutting down the reactor without any external intervention, causing the self-shutdown behavior.

Figure 3: Behavior of power as a function of time

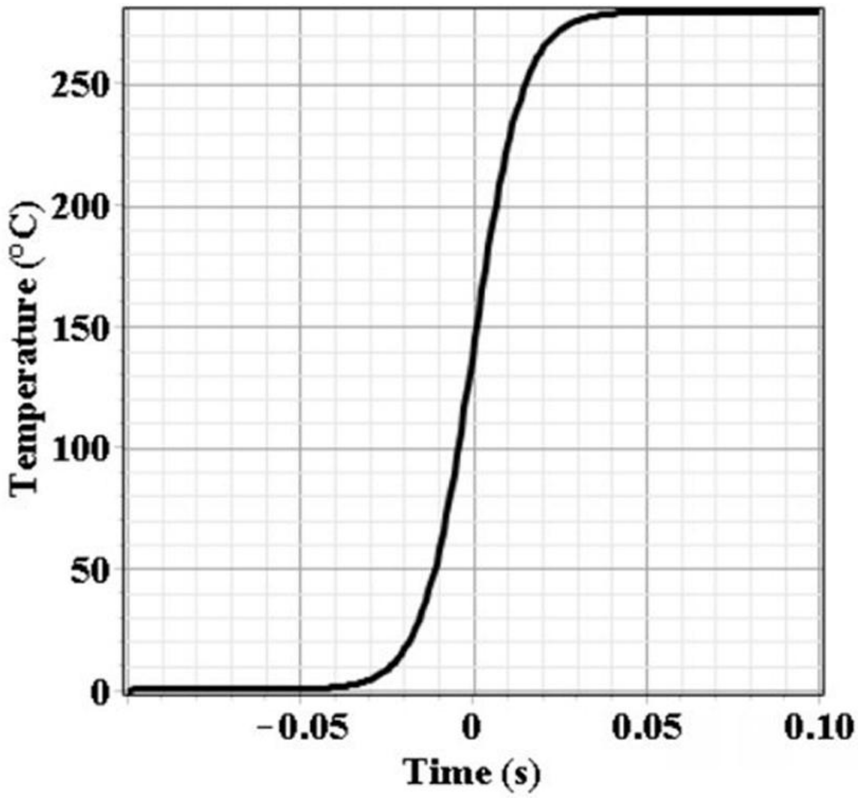


Source: Author

Prior to t ≈ -0.05 s, the power remains negligible, as the prompt chain reaction has not yet developed. As the inserted reactivity drives the reactor prompt supercritical, the power increases sharply, reaching a peak of 297 MW at t ≈ 0 s. This high peak power is a direct consequence of the large reactivity insertion, which drives a rapid and intense prompt neutron chain reaction.

Following the peak, the power decreases quickly as the negative fuel temperature coefficient of the zirconium hydride fuel introduces sufficient negative reactivity to suppress the chain reaction, characterizing the self-limiting behavior intrinsic to TRIGA® reactors. By t ≈ 0.05 s, the power returns to near-zero levels. This is consistent with the dynamics predicted by the standard Fuchs-Nordheim model, where the temperature feedback acts progressively as energy is deposited in the fuel within milliseconds. [15]

Figure 4: Behavior of temperature as a function of time



Source: Author

Before t ≈ -0.05 s, the variation of temperature remains near zero, which is consistent to the fact that there is no significant power generation at this stage. As the pulse develops, the temperature rises, following the energy deposition profile dictated by the power pulse shown in Figure 3.

The variation of temperature reaches its maximum value of approximately 280 °C at around t ≈ 0.04 s, slightly after the instant of peak power, which is expected since temperature is an integrated response to the energy deposited in the fuel. Following the peak, the temperature stabilizes at this maximum value, as no significant heat removal mechanism is accounted for on the millisecond timescale of the pulse.

This plateau behavior is characteristic of adiabatic models such as Fuchs-Nordheim, where heat losses during the pulse are considered negligible. The rapid temperature rise is the physical mechanism responsible for the self-shutdown of the reactor, as the negative temperature coefficient of the zirconium hydride fuel converts this thermal energy directly into negative reactivity, suppressing the chain reaction as observed in Figure 2.

Regarding the shape and temporal behavior of the pulses, the results of the present work are qualitatively consistent with those of Svajger et al. (2024). In both cases, higher reactivity insertions produce narrower and more intense power pulses, while lower insertions ($1\beta = 0.007$) result in negligible peak power, confirming the threshold-like nature of prompt supercritical pulses.

The pulse profile obtained in the present work closely resembles the Fuchs-Nordheim model results from Svajger et al. (2024), with pulses centered around t ≈ 0 s and a symmetric shape. Regarding peak power values, however, a quantitative discrepancy is observed. For a 3β insertion, Svajger et al. (2024) report a peak power of approximately 1200 MW, while the present work yields approximately 297 MW for the same reactivity insertion. This difference is expected, as peak power in the Fuchs-Nordheim framework is highly sensitive to reactor-specific parameters such as the prompt neutron lifetime (Λ), the effective delayed neutron fraction (β), and the fuel heat capacity.

Overall, the qualitative agreement between the two works (particularly in pulse shape, temporal symmetry, and the monotonic dependence of peak power on inserted reactivity) validates the implementation of the model adopted in the present work. [14]

3.2. Modified Fuchs-Nordheim

With the introduction of the modification in heat capacity, considering Equation 7 as an assumption, a different approach was used, making two main analyses: Power as a function of temperature and Power as a function of reactivity. Both final analytical solutions can be found in Equations 12 and 13:

$$P(T) = \frac{1}{\Lambda}\left[\delta\rho_o aT + (2b\delta\rho_o - \alpha a)\frac{T^2}{2} - 2\alpha b\frac{T^3}{3}\right] \tag{12}$$

$$P(\rho) = -\frac{1}{\alpha\Lambda}\left[-\frac{b\rho^3}{3\alpha} + \frac{\rho^2}{2}\left(a + \frac{b\rho_o + b\beta}{\alpha}\right) - \rho\left(a\beta + \frac{b\beta\rho_o}{\alpha}\right)\right] + \frac{1}{\alpha\Lambda}\left[-\frac{b\rho^3}{3\alpha} + \frac{\rho^2}{2}\left(a + \frac{b\rho_o + b\beta}{\alpha}\right) - \rho\left(a\beta + \frac{b\beta\rho_o}{\alpha}\right)\right] \tag{13}$$

where $\delta\rho_o = \rho_o - \beta$. For graphical solutions, it was considered the same values as given in Table 1 and additional constants, given in Table 2:

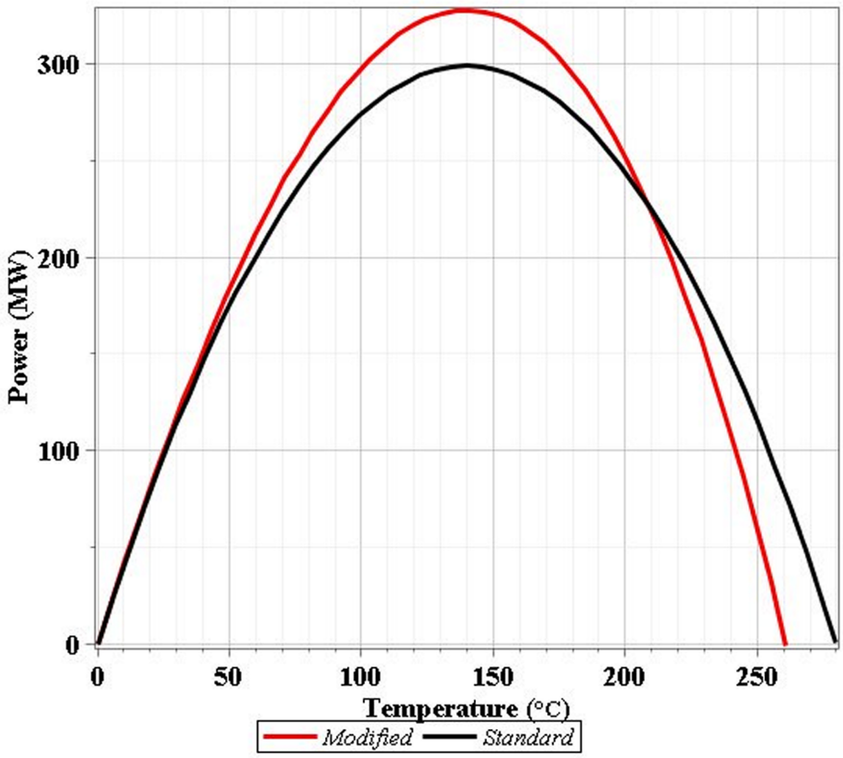
Table 2: Constants used to obtain the graphical pulse behavior in modified Fuchs-Nordheim

Constant used	Values
a	30380.72851
b	65.1736558

Source: [15]

We evaluate the power profile as a function of both temperature and reactivity, as displayed in Figures 4 and 5, respectively.

Figure 5: Behavior of Power as a function of Temperature



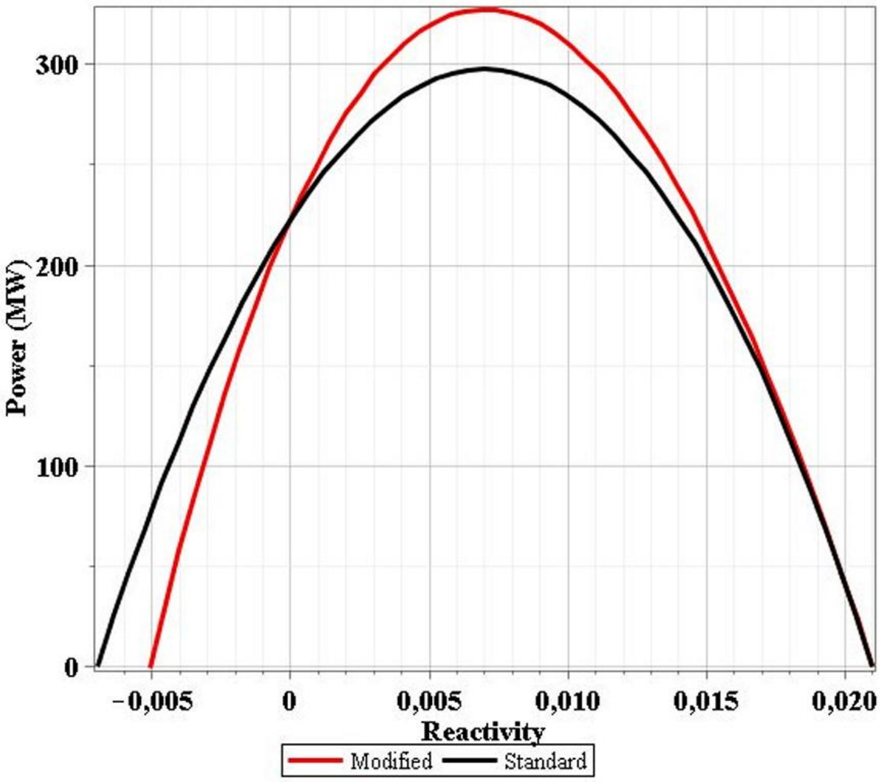
Source: Author

Both models reach their peak power at approximately the same fuel temperature of 140°C, confirming that the temperature at peak power is largely determined by the reactor's intrinsic parameters and is not significantly affected by the heat capacity formulation. However, the magnitude of the peak differs: the modified model yields a peak power of 327 MW, while the standard model reaches 297 MW, a difference of approximately 10%.

The result indicates that, at the same fuel temperature, the modified model predicts a more intense neutron chain reaction, a direct consequence of the lower effective heat capacity at intermediate temperatures, which allows more energy to be deposited in the fuel for a given temperature rise.

On the descending side, the two curves diverge, with the standard model returning to zero power at approximately 260°C, while the modified model extends to approximately 280°C. The difference in final temperature reflects the greater total energy deposited in the fuel during the modified model pulse, consistent with its higher peak power and broader power profile.

Figure 6: Behavior of power as a function of reactivity



Source: Author

In both curves, power rises as reactivity decreases from its maximum inserted value (0.021), reaching a peak near the prompt critical threshold, and subsequently returns to zero as the negative temperature feedback drives the reactivity to its residual negative value (~ -0.007). They also reach their maximum power level at approximately the same reactivity value of ~0.007, consistent with the prompt critical condition.

However, the modified model yields a notably higher peak power of 327 MW compared to 297 MW for the standard model, representing a difference of approximately 10%. This discrepancy reflects the effect of the temperature-dependent heat capacity incorporated in the modified model: as the fuel temperature rises, the increasing heat capacity alters the energy balance of the pulse, allowing a more intense chain reaction to develop before the feedback mechanism is sufficient to suppress it.

On the ascending side of the curve, the modified model rises more steeply at lower reactivity values, indicating higher power generation even before the peak is reached. On the descending side, both curves converge toward zero power at the maximum inserted reactivity (0.021), with the modified model exhibiting a slightly wider loop, consistent with its greater total energy deposition during the pulse.

4. CONCLUSIONS

The present manuscript evaluated a Fuchs-Nordheim model including heat capacity variation for a TRIGA® reactor through the implementation and comparison of the standard and modified mathematical modelling.

In the standard model, analysis of the reactivity behavior as a function of time demonstrated that the self-limiting mechanism intrinsic to TRIGA® reactors operates effectively, with the reactivity decreasing sharply from its initial inserted value of 0.021 to a residual negative value of approximately -0.007, driven exclusively by the negative fuel temperature coefficient of the zirconium hydride fuel. This behavior confirms that no external shutdown system is required to terminate the pulse, a fundamental safety feature of TRIGA® reactors.

The power pulse profiles obtained from both models, it is exhibited the expected sharp rise and rapid decay, which is characteristic of prompt supercritical pulses, with peak power occurring at $t \approx 0$ s. The standard model yielded a peak power of approximately 297 MW, while the modified model predicted a higher value of approximately 327 MW, reflecting the influence of the temperature-dependent heat capacity introduced in the modification.

The phase-space analysis of power as a function of both temperature and reactivity reinforced these findings. Both models predicted peak power at a fuel temperature of 140°C and a reactivity of approximately 0.007, with the modified model consistently yielding higher power levels throughout the pulse. The broader loop traced by the modified model in both phase spaces confirms its prediction of greater total energy deposition during the pulse.

Comparison with the results reported by Svajger et al. (2024) revealed qualitative agreement in pulse shape, temporal symmetry, and the monotonic dependence of peak power on inserted reactivity. The quantitative differences observed, particularly in absolute peak power values are attributable to the distinct reactor-specific parameters employed in each work, namely the prompt neutron lifetime, effective delayed neutron fraction, and fuel heat capacity utilized on the JSI TRIGA® Mark II reactor.

The results demonstrate that the modified Fuchs-Nordheim model provides a more physically consistent description of TRIGA® pulse dynamics by accounting for the temperature dependence of heat capacity, while both models successfully capture the essential self-limiting behavior of the reactor. These findings contribute to the validation of analytical pulse models for the other reactors and provide a basis for future comparisons with experimental pulse data.

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CONTRIBUTORSHIP

Conceptualization: B.K.D, V.O.S

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Writing – review and editing: B.K.D, V.O.S, R.G.C., P.C.R.S.

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

Interview transcripts and qualitative data are not publicly available due to confidentiality commitments made to research participants. Aggregated data supporting the findings are available from the corresponding author upon reasonable request and subject to participant privacy protections.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY. **History, Development and Future of TRIGA Research Reactors**. Technical Reports Series No. 482. Vienna: IAEA, 2016. Disponível em: https://www.iaea.org/publications/10798/history-development-and-future-of-triga-research-reactors. Acesso em: 07 jan. 2026

[2] AMAZUL. **Reatores nucleares de pesquisa no Brasil**. 2026. Disponível em: https://www.amazul.mar.mil.br/reatores-nucleares-de-pesquisa-no-brasil. Acesso em: 07 jan. 2026.

[3] GENERAL ATOMICS. **TRIGA Nuclear Reactors**. 2026. Disponível em: https://www.ga.com/triga-nuclear-reactors. Acesso em: 07 jan. 2026.

[4] COMISSÃO NACIONAL DE ENERGIA NUCLEAR. **Por dentro do reator TRIGA**. Centro de Desenvolvimento da Tecnologia Nuclear – CDTN, 2022. Disponível em: https://www.cdtn.br/por-dentro-do-reator-triga. Acesso em: 13 jan. 2026.

[5] WORLD NUCLEAR NEWS. **TRIGA International to produce fuel for US microreactor**. 2023. Disponível em: https://www.world-nuclear-news.org/articles/triga-international-to-produce-fuel-for-us-microreactor. Acesso em: 13 jan. 2026.

[6] MESQUITA, A. Z.; REZENDE, H. C. Thermal methods for on-line power monitoring of the IPR-R1 TRIGA Reactor. **Progress in Nuclear Energy** (New Series), v. 52, p. 268-272. 2010. DOI: 10.1016/j.pnucene.2009.07.013.

[7] MESQUITA, A .Z. *et al*. Experimental Investigation of Thermal Hydraulics in the IPR-R1 TRIGA Nuclear Reactor. In: Amir Z. Mesquita (Ed).; **Nuclear Reactors**. 1ed. v. 1, p. 1-24. ISBN: 978-953-51-0018-8, InTech, 2012. DOI: 10.5772/25869.

[8] GENERAL ATOMICS. **TRIGA Fuels**. 2026. Disponível em: https://www.ga.com/triga-fuels. Acesso em: 07 jan. 2026.

[9] MESQUITA, A.Z.; REZENDE, H.C.; RODRIGUES, R.R.; ALMEIDA, V.F.; PALMA, D.A.P. Experimental evaluation of natural convection in the IPR-R1 Triga research reactor at 264 kW and 105 kW. **Brazilian Journal of Radiation Sciences**, 09-02B, p. 01-15, 2021. DOI: https://doi.org/10.15392/bjrs.v9i2B.1256

[10] MESQUITA, A.Z. et al. PROPOSTA DE UTILIZAÇÃO DO REATOR NUCLEAR DE PESQUISA TRIGA IPR-R1 DO CENTRO DE DESENVOLVIMENTO DA TECNOLOGIA NUCLEAR (CDTN) EM PESQUISA E TREINAMENTO**. VI Congresso Nacional de Engenharia Mecânica**, **Associação Brasileira de Engenharia e Ciências Mecânicas**, 2010. Disponível em: Microsoft Word - Fullconem2010 CDTN.doc Acesso em: 07 jan. 2026

[11] GENERAL ATOMICS. **GA Fuels**. Disponível em: https://www.ga.com/combustiveis-triga. Acesso em: 13 jan. 2026.

[12] PAXTON, H. C. **Glossary of Nuclear Criticality Terms**. Los Alamos: Los Alamos National Laboratory, 1989. Disponível em: https://osti.gov/servlets/purl/5609066-o4S1LS/. Acesso em: 13 jan. 2026.

[13] HOLSCHUH, T. V.; MARCUM, W. R. Modified Fuchs-Nordheim model for use in reactor pulse measurements. **Annals of Nuclear Energy**, v. 116, p. 314-318, 2018. DOI: https://doi.org/10.1016/j.anucene.2018.02.040

[14] MAGALHÃES, W. F. et al. **Físico-Química I: Termodinâmica do Equilíbrio**. Belo Horizonte: Universidade Federal de Minas Gerais, Departamento de Química, ICEx, Setor de Físico-Química, 2009. Disponível em: Microsoft Word - YAula8CalorClean. Acesso em: 07 jan. 2026.

[15] SVAJGER et al. Evaluation of reactor pulse experiments. **Nuclear Engineering and Technology**, v. 56, p. 1165-1203, 2024. DOI: https://doi.org/10.1016/j.net.2023.11.021

[16] DUDERSTADT, J. J.; HAMILTON, L. J. **Nuclear Reactor Analysis**. United States of America: John Wiley & Sons Inc., 1976.

[17] NRC. **Kinetic Behavior of TRIGA Reactors**. Conference on Utilization of Research Reactors, GA-7882. 1967. Disponível em: GA-7882, Kinetic Behavior of TRIGA Reactors. Acesso em: 13 jan. 2026.

[18] SCALETTAR, R. The Fuchs-Nordheim model with variable heat capacity. **Nuclear Science and Engineering**, v. 16, n. 4, p. 459-460, 1963. DOI: https://doi.org/10.13182/NSE63-A26559

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