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Generalized Point Reactor Kinetics

Oyama[a*], A. L. Y. V.; da Silva[b], A. C; Gonçalvez[b], A. C.; Martinez[b], A. S.

[a] Nuclear Engineering Department - POLI/UFRJ, 21941-914, Rio de Janeiro, Brazil.
[b] Nuclear Engineering Program - COPPE/UFRJ, 21941-914, Rio de Janeiro, Brazil.

*Correspondence: andreoyama@poli.ufrj.br

Abstract: In this paper, we are proposing a generalized analytical solution to the point reactor kinetics equations for six groups of delayed neutron precursors for both conventional and subcritical equations. The methodology presented aims to obtain an analytical solution using the similarity transformation technique. This solution will make it possible to evaluate the behavior of the nuclear reactor power as a function of time, for a given constant reactivity inserted in the reactor core, in a very simple way and without computational effort, compared to numerical solutions. The results obtained will be compared with reference methods to validate the methodology presented in this paper.

Keywords: point reactor kinetics, reactor power, analytical solution, conventional and subcritical equations, similarity transformation.

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Cinética Pontual de Reatores Generalizada

Resumo: Neste artigo, propomos uma solução analítica generalizada para as equações da cinética pontual de reatores para seis grupos de precursores de nêutrons atrasados tanto para as equações convencionais quanto para as equações subcríticas. A metodologia apresentada visa a obtenção de uma solução analítica usando técnica de transformação de similaridade. Esta solução permitirá avaliar o comportamento da potência do reator nuclear em função do tempo, para uma dada reatividade constante inserida no núcleo do reator, de forma bastante simples e sem esforço computacional, em comparação com as soluções numéricas. Os resultados obtidos serão comparados com os métodos de referência para validar a metodologia apresentada neste artigo.

Palavras-chave: cinética pontual de reatores, potência do reator; solução analítica, equações convencional e subcrítica, transformação de similaridade.

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1. INTRODUCTION

The point reactor kinetics equations [1,2,3] are set of seven linear time-depend differential equations, in which the only parameter that depends on time is reactivity, $\rho(t)$. These equations make it possible to evaluate the behavior of nuclear power, $P(t)$, as well as delay neutron precursor concentrations, $C_i(t)$, under different conditions, such as: fast transients as a result of a given reactivity insertion in the reactor core, such as the movement or fall of control rods in the reactor core. With this, it is possible to evaluate the reactor's power behavior as a function of time, for normal operation, transients and even accidents.

The analysis of the temporal behavior of power, $P(t)$, is of vital importance, because allows to evaluate the growth of the neutron population in short or long-time intervals, i.e., in fast transients, as well as predicting possible accidents due to sudden changes in the multiplication of neutrons in the reactor. It is worth remembering that these equations can also be used to evaluate possible postulated accidents, the aim of which is to understand the limits of insertion of reactivity into the reactor core that could compromise its integrity.

Since these are analytical solutions, the computational effort required to carry out different simulations is reduced to zero when compared to the numerical solutions implemented to solve the same problem with a time step of the order of the lifetime of the ready neutrons, l_p, i.e., $\Delta t = 10^{-4} s$. The results obtained in this paper will be compared with those found in the literature to validate this proposal.

2. GENERALIZED POINT REACTOR KINETICS EQUATIONS

The generalized point reactor kinetics equations, for six groups of neutron precursors, including the external source term, are given by:

$$\frac{d}{dt}P(t) = \gamma P(t) + \sum_{i=1}^{6} \tilde{\lambda}_i C_i(t) + Q \tag{1}$$

$$\frac{d}{dt}C_i(t) = \xi_i P(t) - \hat{\lambda}_i C_i(t), \qquad i = 1, \ldots, 6, \tag{2}$$

where γ, $\tilde{\lambda}_i$, $\hat{\lambda}_i$ and ξ_i are the kinetic parameters calculated for each type of system of interest, $P(t)$ is the power, $C_i(t)$, the i-th term of the neutron precursor concentration and Q the external source. For the conventional equations, the external source term is zero.

Thus, the Eqs. (1) and (2) in the matrix form are:

$$\frac{d}{dt}\overbrace{\begin{pmatrix} P(t) \\ C_1(t) \\ C_2(t) \\ C_3(t) \\ C_4(t) \\ C_5(t) \\ C_6(t) \end{pmatrix}}^{\boldsymbol{P}(t)} = \overbrace{\begin{pmatrix} \gamma & \tilde{\lambda}_1 & \tilde{\lambda}_2 & \tilde{\lambda}_3 & \tilde{\lambda}_4 & \tilde{\lambda}_5 & \tilde{\lambda}_6 \\ \xi_1 & -\hat{\lambda}_1 & & & & & \\ \xi_2 & & -\hat{\lambda}_2 & & & & \\ \xi_3 & & & -\hat{\lambda}_3 & & & \\ \xi_4 & & & & -\hat{\lambda}_4 & & \\ \xi_5 & & & & & -\hat{\lambda}_5 & \\ \xi_6 & & & & & & -\hat{\lambda}_6 \end{pmatrix}}^{\boldsymbol{M}} \overbrace{\begin{pmatrix} P(t) \\ C_1(t) \\ C_2(t) \\ C_3(t) \\ C_4(t) \\ C_5(t) \\ C_6(t) \end{pmatrix}}^{\boldsymbol{P}(t)} + \overbrace{\begin{pmatrix} Q \\ \\ \\ \\ \\ \\ \end{pmatrix}}^{\boldsymbol{Q}}. \tag{3}$$

As we can see, the point reactor kinetics equations constitute a system of 7 ordinary differential equations whose kinetic parameters, in this case, are constant. Rewriting the Eq. (3) using matrix notations, we get

$$\frac{d}{dt}\boldsymbol{P}(t) = \boldsymbol{M}\boldsymbol{P}(t) + \boldsymbol{Q}, \tag{4}$$

where $\boldsymbol{P}(t)$ is a vector containing the power and concentration of neutron precursors, $\boldsymbol{M}$ the matrix with the kinetic parameters and $\boldsymbol{Q}$ a vector with the external source.

To solve this system of equations, we can assume that the general solution [4] is a linear combination of a particular solution combined with a homogeneous solution, such that

$$\boldsymbol{P}(t) = \boldsymbol{P}^{hom}(t) + \boldsymbol{P}^{part}(t). \tag{5}$$

According to the techniques for solving ordinary differential equations, the particular solution has the form of the external source. In this case, as the source is constant, we can assume that $\boldsymbol{P}^{part}(t) = \boldsymbol{P}^{part}$. Therefore, we have

$$\frac{d}{dt}\boldsymbol{P}^{part} = 0,$$

so, we have

$$\boldsymbol{P}^{part} = -\boldsymbol{M}^{-1}\boldsymbol{Q}, \tag{6}$$

where $\boldsymbol{M}^{-1}$ is the inverse of the kinetic parameter matrix.

We will now turn our attention to the homogeneous solution such that:

$$\frac{d}{dt}\boldsymbol{P}^{hom}(t) = \boldsymbol{M}\boldsymbol{P}^{hom}(t). \tag{7}$$

We can decouple the system of equations given by Eq. (7) using the Similarity Transformation [5,6]. To do this, let's assume that $P^{hom}(t)$ is expressed by the product of a matrix $\mathbf{T}_{7x7}$, whose columns are the eigenvectors of the matrix $\mathbf{M}_{7x7}$, by a column vector $\boldsymbol{p}(t)$. Thus, we have

$$\boldsymbol{P}^{hom}(t) = \mathbf{T}\boldsymbol{p}(t). \tag{8}$$

Substituting Eq. (8) into (7), we get

$$\frac{d}{dt}\big(\mathbf{T}\boldsymbol{p}(t)\big) = \boldsymbol{M}\big(\mathbf{T}\boldsymbol{p}(t)\big) \quad \therefore \quad \mathbf{T}\frac{d}{dt}\boldsymbol{p}(t) = \boldsymbol{M}\mathbf{T}\boldsymbol{p}(\boldsymbol{t}),$$

and multiplying this result by the inverse matrix of eigenvectors, it follows that

$$\mathbf{T^{-1}T}\frac{d}{dt}\boldsymbol{p}(t) = \mathbf{T^{-1}}\boldsymbol{M}\mathbf{T}\boldsymbol{p}(t),$$

where $\mathbf{T^{-1}T} = \mathbf{I}$, i.e., the identity matrix and $\mathbf{T^{-1}}\boldsymbol{M}\mathbf{T} = \mathrm{diag}(\lambda_j)$ is a well-known relation associated with eigenvalue end eigenvector problems, where $\mathrm{diag}(\lambda_j)$ is a diagonal matrix containing the eigenvalues of the $\boldsymbol{M}$ matrix. This calculation allows the equations to be decoupled, so that:

$$\frac{d}{dt}p_j(t) = \lambda_j p_j(t), \quad j = 1, \ldots, 7, \tag{9}$$

whose solution to Eq. (9) is well known in the literature and is given by

$$p_j(t) = a_j e^{\lambda_j t}, \quad j = 1, \ldots, 7. \tag{10}$$

As a result, the homogeneous solution becomes

$$\boldsymbol{P}^{hom}(t) = \mathbf{T}\boldsymbol{p}(t), \tag{11}$$

where, in matrix form, we have that

$$\begin{pmatrix} P_1^{hom}(t) \\ P_2^{hom}(t) \\ P_3^{hom}(t) \\ P_4^{hom}(t) \\ P_5^{hom}(t) \\ P_6^{hom}(t) \\ P_7^{hom}(t) \end{pmatrix} = \begin{pmatrix} T_{11}T_{12}T_{13}T_{14}T_{15}T_{16}T_{17} \\ T_{21}T_{22}T_{23}T_{24}T_{25}T_{26}T_{27} \\ T_{31}T_{32}T_{33}T_{34}T_{35}T_{36}T_{37} \\ T_{41}T_{42}T_{43}T_{44}T_{45}T_{46}T_{47} \\ T_{51}T_{52}T_{53}T_{54}T_{55}T_{56}T_{57} \\ T_{61}T_{62}T_{63}T_{64}T_{65}T_{66}T_{67} \\ T_{71}T_{72}T_{73}T_{74}T_{75}T_{76}T_{77} \end{pmatrix} \begin{pmatrix} p_1(t) \\ p_2(t) \\ p_3(t) \\ p_4(t) \\ p_5(t) \\ p_6(t) \\ p_7(t) \end{pmatrix}. \tag{12}$$

Substituting Eq. (10) into (12), we get

$$\begin{pmatrix} P_1^{hom}(t) = \sum_{j=1}^{7} T_{1j} a_j \mathrm{e}^{\lambda_j t} \\ P_2^{hom}(t) = \sum_{j=1}^{7} T_{2j} a_j \mathrm{e}^{\lambda_j t} \\ P_3^{hom}(t) = \sum_{j=1}^{7} T_{3j} a_j \mathrm{e}^{\lambda_j t} \\ P_4^{hom}(t) = \sum_{j=1}^{7} T_{4j} a_j \mathrm{e}^{\lambda_j t} \\ P_5^{hom}(t) = \sum_{j=1}^{7} T_{5j} a_j \mathrm{e}^{\lambda_j t} \\ P_6^{hom}(t) = \sum_{j=1}^{7} T_{6j} a_j \mathrm{e}^{\lambda_j t} \\ P_7^{hom}(t) = \sum_{j=1}^{7} T_{7j} a_j \mathrm{e}^{\lambda_j t} \end{pmatrix}. \quad (13)$$

Therefore, we have the general solution of Eq. (5),

$$\boldsymbol{P}(t) = \boldsymbol{P}^{hom}(t) + \boldsymbol{P}^{part}, \quad (14)$$

Using the initial condition of the problem, we can set up a system of equations and calculate the coefficients $a_j, j = 1, \dots, 7$. The initial condition of the problem is such that $P(0) = P_0$ and $C_i(0) = \frac{\xi_i P_0}{\tilde{\lambda}_i}$, with $\mathrm{i} = 1, \dots, 6$. This solution can be applied to both conventional and subcritical equations.

3. NUMERICAL RESULTS AND DISCUSSIONS

In this section we will make some applications using the generalized point reactor kinetics equations. Before presenting the results obtained, we will validate the results obtained in both cases.

3.1. Conventional Point Reactor Kinetics Equations

The first analysis of results consists of evaluating the behavior of the power for some constant reactivity values inserted in the reactor core. In this case, the external neutron source term is null and the kinetic parameters of Eq. (1) and (2) are defined in such a way as to obtain the conventional point reactor kinetic equations for six groups of neutron precursors [7]:

$$\frac{d}{dt}P(t) = \left(\frac{\rho_o - \beta}{\Lambda}\right)P(t) + \sum_{i=1}^{6}\lambda_i C_i(t) \tag{15}$$

$$\frac{d}{dt}C_i(t) = \frac{\beta_i}{\Lambda}P(t) - \lambda_i C_i(t), \qquad i = 1, \ldots, 6. \tag{16}$$

such that

$$\gamma \equiv \frac{\rho_o - \beta}{\Lambda}, \tag{17}$$

$$\xi_i \equiv \frac{\beta_i}{\Lambda}, \tag{18}$$

$$\tilde{\lambda}_i \equiv \lambda_i, \tag{19}$$

$$\hat{\lambda}_i \equiv \lambda_i, \tag{20}$$

$$Q = 0, \tag{21}$$

where ρ_o is the reactivity, β the total fraction of delayed neutrons, Λ the average neutron generation time, β_i the i-th delayed neutron fraction term, λ_i the i-th decay constant term and Q the external neutron source term.

The kinetic parameters are such that [8]: $\Lambda\,(s) = 0.00002$, $\beta = 0.007$, $\beta_1 = 0.000266$, $\beta_2 = 0.001491$, $\beta_3 = 0.001316$, $\beta_4 = 0.002849$, $\beta_5 = 0.000896$, $\beta_6 = 0.000182$, $\lambda_1\,(s^{-1}) = 0.0127$, $\lambda_2\,(s^{-1}) = 0.0317$, $\lambda_3\,(s^{-1}) = 0.115$, $\lambda_4\,(s^{-1}) = 0.311$, $\lambda_5\,(s^{-1}) = 1.4$ e $\lambda_6\,(s^{-1}) = 3.87$. The initial condition of the problem is such that: $P(0) = 1$ and $C_i(0) = \frac{\beta_i}{\Lambda\lambda_i}$, with $\mathrm{i} = 1, \ldots, 6$.

Tables 1 and 2 present the results obtained for reactor power for some reactivity values, such that reference values presented were obtained using the Finite Difference Method [8], as well the relative error, define by:

$$\epsilon(\%) = \left|\frac{P_{Ref} - P_{Gen}}{P_{Ref}}\right| \times 100. \tag{22}$$

Table 1 : Power, $P(t)$, for reactivity, $\rho_o = 0.003$, for Conventional Kinetics.

Time (s)	Generalized Kinetics	Reference [8]	$\epsilon(\%)$
1	2.2098	2.2098	0%
10	8.0192	8.0192	0%
20	2.8297x10¹	2.8297x10¹	0%

Table 2 : Power, $P(t)$, for reactivity, $\rho_o = 0.007$, for Conventional Kinetics.

Time (s)	Generalized Kinetics	Reference [8]	$\epsilon(\%)$
0.01	4.5088	4.5088	0%
0.5	5.3457x10³	5.3457x10³	0%
2	2.0589x10¹¹	2.0589x10¹¹	0%

As we can see, the numerical results shown in tables 1 and 2 are accurate. Another point to highlight is that to obtain the results using analytical modeling, only a single calculation is performed at the desire time. To illustrate, the reference results presented in tables 1 and 2 were obtained with a time step of 10^{-6}s. So, to simulate a time of 1s, 1 million calculations are needed, that is, the point kinetics equations are solved 1 million times to simulate a time instant of 1s. This is one of the great advantages of using analytical solutions when they are possible to obtain.

3.2. Subcritical Point Reactor Kinetics Equations

For subcritical systems, we can validate Eqs. (1) and (2) as a function of the contribution of the external source term, in order to compensate for the reactivity inserted in the reactor core. To do this, let's assume that the rate of change of the power and precursor concentration are zero at $t = 0$. Therefore, the external source term can be defined as follows:

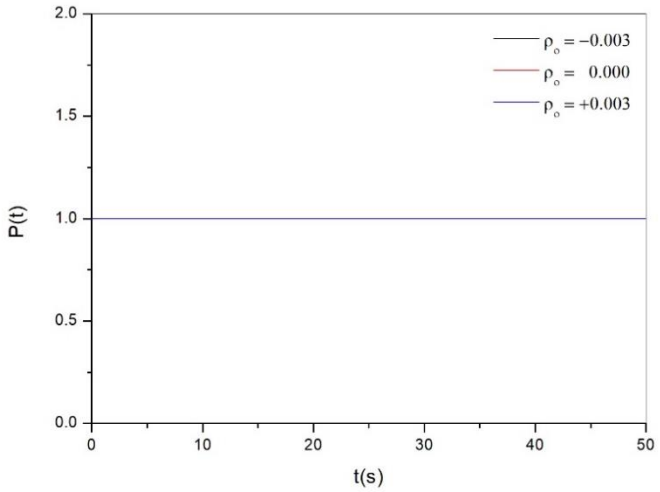
$$Q \equiv -P(0)\left(\gamma + \sum_{i=1}^{6} \xi_i\right). \tag{23}$$

If we use the definitions of reactor kinetics parameters in Eqs. (17) and (18), we obtain the following equation:

$$Q = -\frac{\rho_o}{\Lambda} P(0), \tag{24}$$

where due the negative sign in Eq. (24), the external source term will contribute in the opposite direction to the reactivity insertion, such that: If $\rho_o < 0$, the external source, Q, will be positive, helping to compensate for the negative reactivity and keep the power constant. If $\rho_o = 0$, the external source, Q, will also be zero and the power will remain constant over time. If $\rho_o > 0$, external source, Q, will be negative, preventing the power from increasing due to the reactivity being positive, as shown in Figure 1.

Figure 1: Power, $P(t)$, constant for different reactivity values, ρ_o.



The results shown in Figure 1 were obtained using kinetic parameters presented in section 3.1 and the same initial condition.

3.3. Models proposed by Gandini, Dulla and Gonçalves

With the emergence of ADS-type reactor designs, new models based on point reactor kinetics have been proposed to suit this type of reactor, which combines the subcritical core of a nuclear reactor with a particle accelerator that emits a beam of protons in a spallation source to produce neutrons. This combination (reactor + particle accelerator) has interesting characteristics from the point of view safety and waste management, as it has a high power to transmute materials from high activity to low activity [9,10] and due to its subcritical core, this reactor is inherently safe. The MYRRHA reactor [11], the first ADS-type reactor, is expected to start operating in 2026. In this sense, different models for the point kinetics of reactors have been developed over the years, such as: Gandini [9], Dulla [12], Nishihara [13], Silva [14] and Gonçalves [15] among others. The main difference in obtaining these models is in the definitions of the importance function with the levels of subcriticality and with the external neutron source term.

The Eqs. (25) and (26), represent a generalization of the models proposed by Gandini [9], Dulla [12] and Gonçalves [15], where the main difference is associated with the importance function that is used the calculations of the subcritical kinetic parameters, such that:

$$\Lambda \frac{d}{dt} P(t) = (\rho_o - \beta + \Gamma) P(t) + \sum_{i=1}^{6} \lambda_i C_i(t) + q \tag{25}$$

$$\frac{d}{dt} C_i(t) = \beta_i P(t) - \lambda_i C_i(t), \qquad i = 1, \ldots, 6. \tag{26}$$

such that

$$\gamma \equiv \frac{\rho_o - \beta + \Gamma}{\Lambda}, \tag{27}$$

$$\xi_i \equiv \beta_i, \tag{28}$$

$$\tilde{\lambda}_i \equiv \frac{\lambda_i}{\Lambda}, \tag{29}$$

$$\hat{\lambda}_i \equiv \lambda_i,$$

$$Q \equiv \frac{q}{\Lambda}. \tag{30}$$

Using the initial condition of the problem, such that: $P(0) = 1$ and $C_i(0) = \frac{\beta_i}{\lambda_i}$, with $i = 1, \ldots, 6$ and the kinetic parameters in Tables 3 and 4, under different conditions of subcriticality, we can evaluate the behavior of the reactor's power over time, as shown in Figures 2 and 3. In these example cases, we can see that the power varies rapidly with time and then shows asymptotic behavior. Subcritical reactivity is calculated as follows:

$$\rho_o = 1 - \frac{1}{k_{eff}} \tag{31}$$

Table 3 : Kinetic parameters obtained for the effective multiplication factor, $k_{eff} = 0.95$.

Parameters	Dulla	Gandini	Gonçalves
Λ	1.58243x10^{-3}	1.58284x10^{-3}	1.59587x10^{-3}
Γ	-4.96486x10^{-2}	-4.96521x10^{-2}	-5.25452x10^{-2}
Q	4.96485x10^{-2}	4.96521x10^{-2}	5.25452x10^{-2}
β_1	2.49544x10^{-4}	2.49599x10^{-4}	2.49692x10^{-4}
β_2	1.39832x10^{-3}	1.39861x10^{-3}	1.39911x10^{-3}
β_3	1.23527x10^{-3}	1.23556x10^{-3}	1.23604x10^{-3}
β_4	2.66929x10^{-3}	2.66980x10^{-3}	2.67064x10^{-3}
β_5	8.39949x10^{-4}	8.40121x10^{-4}	8.40406x10^{-4}
β_6	1.70852x10^{-4}	1.70616x10^{-4}	1.70673x10^{-4}
β	6.56296x10^{-3}	6.56431x10^{-3}	6.56656x10^{-3}

Table 4 : Kinetic parameters obtained for the effective multiplication factor, $k_{eff} = 0.98$.

Parameters	Dulla	Gandini	Gonçalves
Λ	1.52602x10^{-3}	1.52618x10^{-3}	1.52969x10^{-3}
Γ	-1.98505x10^{-2}	-1.98512x10^{-2}	-2.03282x10^{-2}
Q	1.98505x10^{-2}	1.98512x10^{-2}	2.03282x10^{-2}
β_1	2.49724x10^{-4}	2.49746x10^{-4}	2.49725x10^{-4}
β_2	1.39926x10^{-3}	1.39938x10^{-3}	1.39927x10^{-3}
β_3	1.23620x10^{-3}	1.23631x10^{-3}	1.23620x10^{-3}
β_4	2.67093x10^{-3}	2.67113x10^{-3}	2.67094x10^{-3}
β_5	8.40504x10^{-4}	8.40572x10^{-4}	8.40507x10^{-4}
β_6	1.70692x10^{-4}	1.70706x10^{-4}	1.70693x10^{-4}
β	6.56730x10^{-3}	6.56784x10^{-3}	6.56733x10^{-3}

We can see in Tables 3 and 4 that the kinetic parameters obtained by Dulla and Gandini show small deviations each other. As a consequence, we have the superimposed graphs for $P(t)$ in Figures 2 and 3. The deviations shown in Figures 2 and 3 by Gonçalves are mainly associated with the values obtained for the kinetic parameters: Λ, Γ and the source term, Q, as they were taken from Tables 3 and 4. Another point to note is that these deviations decrease as we approach criticality.

Figure 2: Power, $P(t)$, for the effective multiplication factor, $k_{eff} = 0.95$.

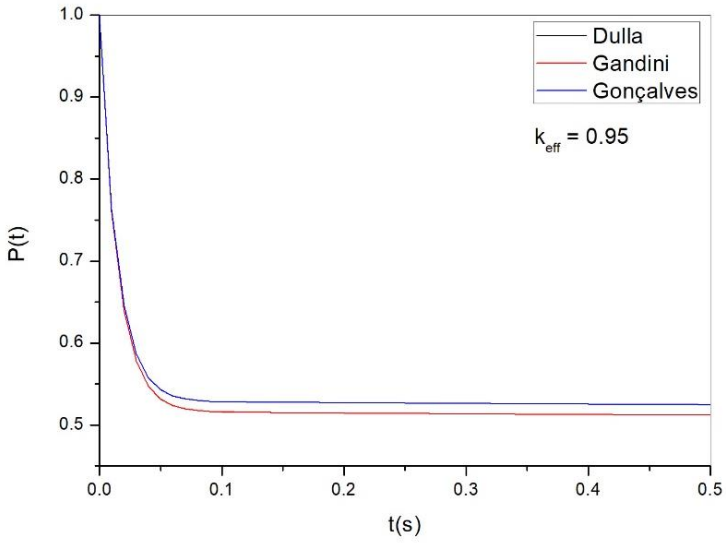
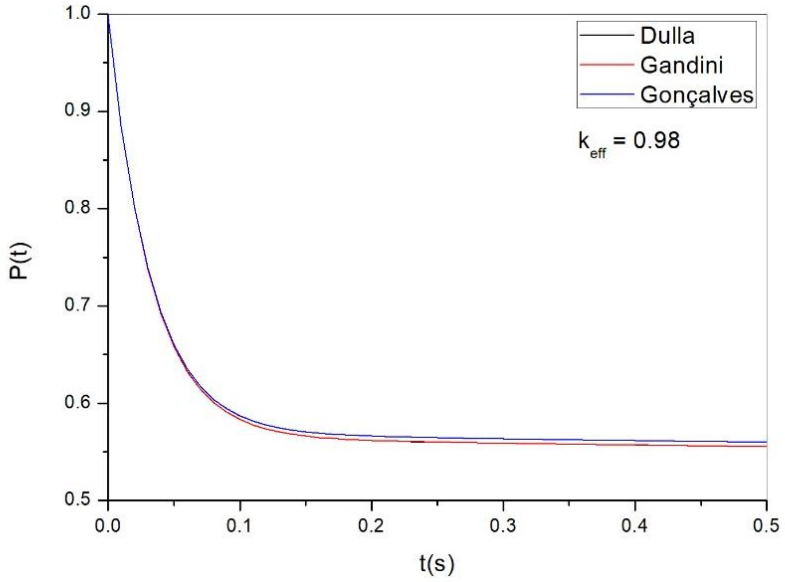


Figure 3: Power, $P(t)$, for the effective multiplication factor, $k_{eff} = 0.98$.



It should be noted that the process of validating the subcritical kinetics presented in section 3.2 can be applied to this section. We can use Eq. (23) to define the external source term that will compensate for the reactivity insert/removed in the reactor core. Take based on Eqs. (25) and (26), we have that: $\gamma = \frac{\rho_o - \beta + \Gamma}{\Lambda}$ and $\xi_i = \beta_i$. Substituting these relations in Eq. (23), the external sources becomes:

$$Q = -(\rho_o + \Gamma)P(0), \tag{32}$$

where the kinetic parameter Γcontributes together with the subcritical reactivity, ρ_o, in the definition of external source term. Therefore, unlike Eq. (24), even if the reactivity is zero, the external source term will not be zero.

4. CONCLUSIONS

The main objective of this paper was to develop a generalized analytical solution for the point reactor kinetics equations for six groups of neutron precursors for both the conventional and subcritical equations. The methodology used was based on concepts involving analytical solutions of ordinary differential equations and the similarity transformation technique.

The results obtained from the generalized point reactor kinetics equations for different kinetics parameters as well as for different reactivity values were presented. In this way, we compared and validated the results with reference values, according Tables 1 and 2. Other results involving the modeling proposed by Gandini, Dulla and Gonçalves are shown in Figures 2 and 3, using the kinetic parameters in tables 3 and 4, respectively.

The results presented in this paper show the feasibility of using generalized point reactor kinetics to evaluate the behavior of the reactor power as a function of time, for a given constant reactivity inserted/removed in the reactor core, in a very simple way and without computational effort, compared to the numerical solutions. Another point in that this modeling can be applied to both the conventional and subcritical equations.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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