Acta Polytechnica **63**(5):356–363, 2023
https://doi.org/10.14311/AP.2023.63.0356

Published by the Czech Technical University in Prague

APPLICATION OF THE SOURCE-JERK METHOD USING A NEUTRON GENERATOR IN A SUBCRITICAL REACTOR

Jan Rataj*, Jakub Mátl, Pavel Suk

Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Department of Nuclear Reactors, Břehová 7, 115 19 Prague, Czech Republic

* corresponding author: jan.rataj@fjfi.cvut.cz

Abstract. This paper describes the application of the Source-Jerk method using a neutron generator in the VR-1 reactor. The experiments were carried out on a shutdown reactor with subcriticality greater than -10 β_{eff}. A D-D neutron generator located in the radial channel of the VR-1 reactor was used as an external neutron source for the Source-Jerk method. The obtained results were discussed and compared with a conventional Source-Jerk method used at the VR-1 reactor and with the values calculated by the Serpent 2 code. The presented experimental works and their results will allow to extend the methods of reactivity measurements on the VR-1 reactor. They will also help to optimise reactivity measurements on the new subcritical reactor VR-2, which is currently being commissioned at the Czech Technical University in Prague.

Keywords: Source-Jerk method, reactivity measurement, experiment, neutron generator, subcritical reactor.

1. Introduction

Reactivity is one of the key operating parameters of a nuclear reactor. It is therefore important to continuously improve the various methods for measuring and determining reactivity. The ability to obtain information on the reactivity of the system is essential for reactor control and maintenance of a fission chain reaction. Therefore, the work presented in this paper focuses on improvement of an experimental reactivity measurement method called the Source-Jerk method.

All of the reactivity measurements described in this paper were performed at the VR-1 training reactor operated at the Czech Technical University in Prague (CTU). The main experimental reactivity measurement methods used at the VR-1 reactor include Source-Jerk (SJ) and Rod-Drop (RD). Both methods are based on perturbation of the neutron population by dropping the control rod (RD) or sudden removal of an external neutron source (SJ). In the case of the VR-1 reactor, the removal of the AmBe radionuclide source, which is part of the reactor control system, has been the standard for the SJ method.

Both the Source-Jerk method and the Rod-Drop method can vary in the way the methods are applied. Two main analysis techniques have been employed in the past: the prompt-drop approximation and the integral-flux method. The prompt-drop approximation neglects the influence of delayed neutrons and depends only on the instantaneous change in neutron flux. This can lead to increased inaccuracy and high statistical error. On the contrary, the integral-flux method does take into account delayed neutrons and depends on the long-term decrease of the neutron population. Below, a brief description of the latter-mentioned technique is presented. The SJ and RD integral flux methods have been found to be highly accurate and can provide a direct measurement of the reactor reactivity [1]. In addition, a variety of technique modifications was proposed; see, e.g. [1, 2]

The main objective of the presented work was the application of the Source-Jerk method using a neutron D-D generator and its comparison with the established reactivity measurement technique using a radionuclide source. The experiments performed and their results will allow one to extend the reactivity measurement methods on the VR-1 reactor. In addition, they will be used to optimise reactivity measurements on the new subcritical reactor VR-2, which is currently being commissioned at CTU [3].

2. Source-Jerk Method

The Source-Jerk method is an experimental reactivity measurement technique used in research reactors to assess subcriticality. The standard assumption of the SJ method is a subcritical core driven by an external static neutron source, while the reactor power remains constant. At time $t = 0$, the neutron source is removed and the neutron population begins to decrease. The reactivity in β_{eff} is given by Equation (1) [1]:

$$\rho(\beta_{\text{eff}}) = \frac{n_0}{\int_0^\infty n(t)\mathrm{d}t}\left[\frac{1}{\beta_{\text{eff}}}\sum_{i=1}^{8}\frac{\beta_{\text{eff},i}}{\lambda_i} + \frac{\Lambda}{\beta_{\text{eff}}}\right], \quad (1)$$

where:

- n_0 is the neutron density before source removal,
- λ_i, β_{eff}, and $\beta_{\text{eff},i}$ are kinetic parameters of the delayed neutrons,
- Λ is the prompt neutron generation time.

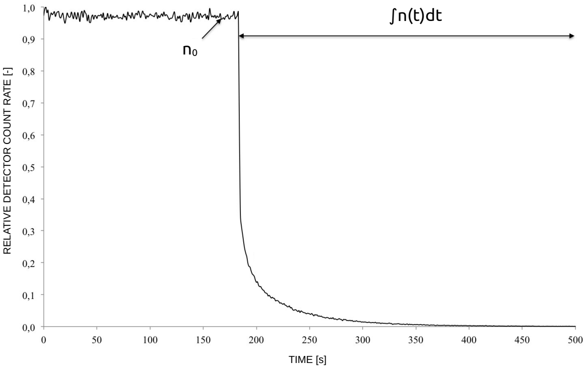

Figure 1. Illustration of the Source-Jerk method [4].

The SJ method is illustrated in Figure 1.

When applying the SJ method, it is necessary to modify Equation (1). In this work, the delayed neutrons were described using an eight-group approximation. For experimental applications, the equation can be modified as follows:

$$\rho(\beta_{\mathrm{eff}}) = \frac{n_0 - n_b}{\int_0^{300\mathrm{s}} (n(t) - n_b)\mathrm{d}t} \left[\frac{1}{\beta_{\mathrm{eff}}} \sum_{i=1}^{8} \frac{\beta_{\mathrm{eff}}}{\lambda_i} \right] , \quad (2)$$

where n_b is the background detector count rate. This modification helps reduce the measurement errors caused by background noise and captures the behaviour of delayed neutrons. Since the mean generation time depends on the criticality of the system, the term $\frac{\Lambda}{\beta_{\mathrm{eff}}}$ was neglected ($\frac{\Lambda}{\beta_{\mathrm{eff}}} \approx 10^{-2} << \sum_{i=1}^{8} \frac{\beta_{\mathrm{eff},i}}{\lambda_i \cdot \beta_{\mathrm{eff}}} \approx 10$). Kinetic parameters λ_i and $\beta_{\mathrm{eff},i}$ were determined using the Serpent2 code; see Section 3.

2.1. Description of the experiment

The main objective of the experiment was to study the advantages and/or disadvantages of the D-D neutron application for the Source-Jerk method.

All experiments were carried out on the VR-1 reactor. The VR-1 reactor (see Figure 2) is a training reactor operated by the Czech Technical University in Prague. It is a light-water reactor with uranium fuel. The fuel is a low-enriched (19.7 % of U-235) uranium fuel of the tube type [5].

The reactor core is housed in a pool-type reactor vessel. The core usually contains 17 to 21 fuel elements depending on the core configuration. The reactor is equipped with several dry vertical channels and one radial channel. The vertical channels are primarily used for the installation of neutron detectors. The radial channel is used mainly for beam experiments [5].

An Am-Be neutron source is used to start up the reactor. It ensures a sufficient level of signal at the output of the power measurement channels for any conditions and guarantees reliable core monitoring during the reactor start-up. The source is placed inside a shielded container below the reactor vessel and is moved pneumatically by pressurised air [5].

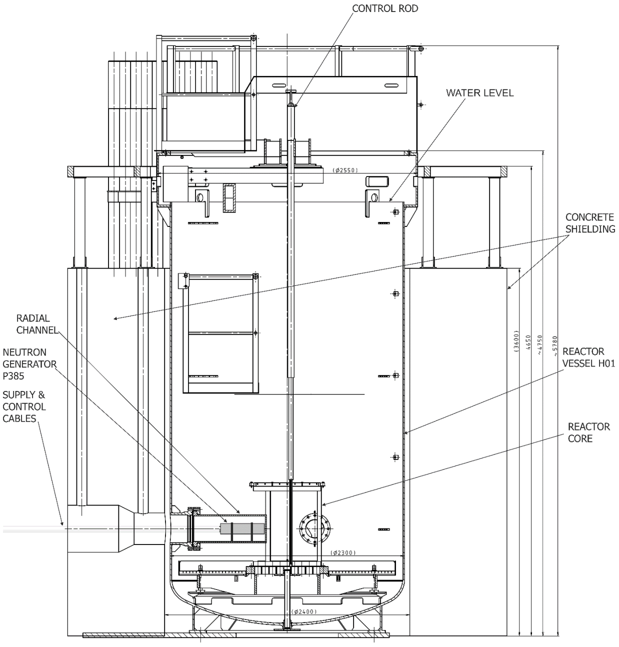

Figure 2. Cross section view of the VR-1 reactor showing location of the neutron generator in the radial channel of the reactor [6].

The VR-1 reactor is classified as a zero power reactor, as its maximum power is 500 W. Reactor power is measured by four fission chambers located around the reactor core in the vertical channels [5].

The VR-1 reactor was used in shutdown mode during the experiments, i.e. the reactivity ρ was less than -10 β_{eff}. Boron-lined detectors SNM-10 and PMV[1] detectors (fission chambers) were used to obtain the count rate (which is proportional to $n(t)$). The detectors were placed in the vertical channels located at different positions in the reactor core (see Figure 3). The boron detectors are portable and can be placed in any vertical channel; fission chambers, as part of the reactor I&C, are fixed in the core [5].

The D-D neutron generator P-385 was placed into the radial channel of the reactor (see Figure 2).

The application of the Source-Jerk method proceeded as follows. First, the average count rate n_0 before the source removal was measured for 300 s. After the neutron source was removed, the integral $\int_0^{300} n(t)\mathrm{d}t$ was determined by numerical integration (trapezoidal rule), and finally, the mean value of n_b was measured (also averaged for 300 s). The same procedure was followed for the AmBe source. The boron detectors were set at 2 different axial positions – at the centre of the core (position S) and at the upper edge of the core (position V); see Figure 4.

The experimental work was divided into two parts: “Preliminary experiment” and “Main experiment”.

---

[1] The detectors are part of the reactor I&C used for operational power measurement.

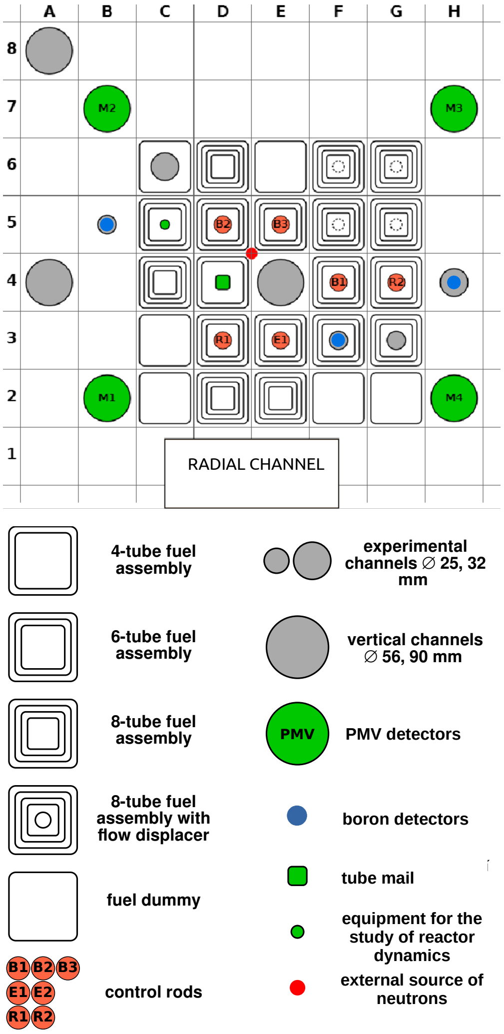

Figure 3. Scheme of the C18 active core configuration [4].

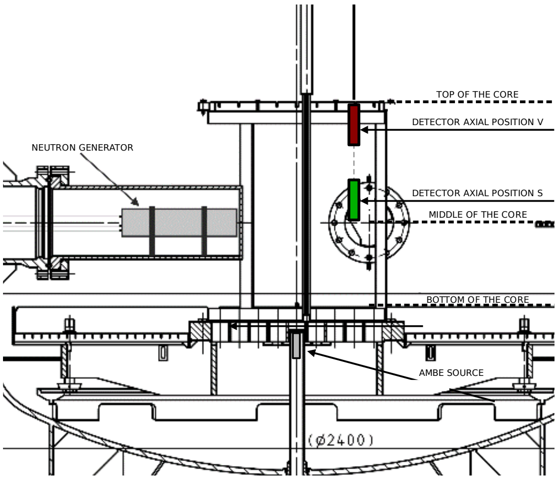

Figure 4. Position of boron-lined detector.

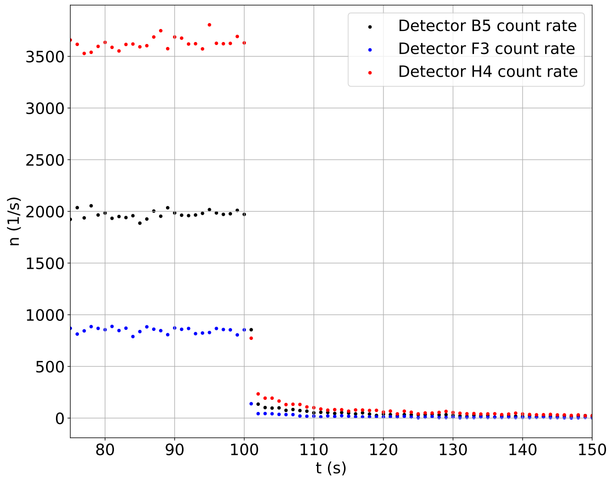

Figure 5. Boron detector count rate at position S with D-D generator [4].

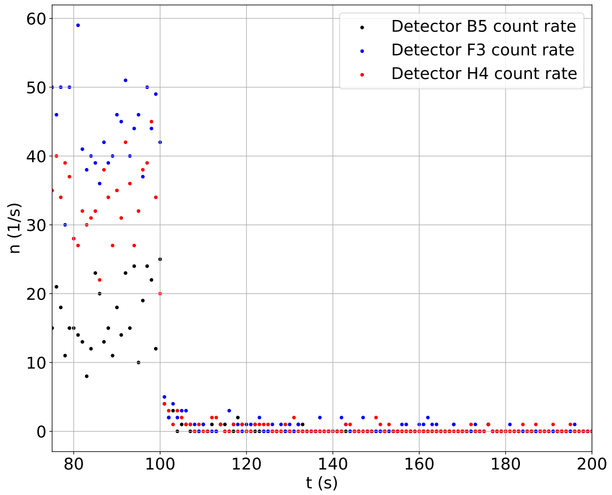

Figure 6. Boron detector count rate at position S with AmBe source [4].

2.2. Preliminary experiment

The aim of the preliminary experiment was to optimise the vertical position of the detectors, compare the results using both neutron sources, and obtain general characteristics of the Source-Jerk method in the deep subcritical regime. It was observed that the detector count rate at position V was low with high relative fluctuations, leading to a significant observational measurement error. This complication made the integral evaluation in Equation (2) difficult to determine and made it unacceptable for the application of the Source-Jerk method. Consequently, position S was established as the default. The use of the neutron D-D generator increased the count rate by about a factor of two, resulting in a lower observational error. The count rate from boron detectors for different neutron sources and vertical positions is illustrated in Figures 5, 6 and 7.

2.3. Main experiment

The main aim of the experiment was to obtain consistent reactivity values in order to compare both neutron sources and discuss their applicability. The time step was set to 1 s and 0.1 s. Both the D-D generator and the AmBe source were used as neutron sources. The results obtained were compared with the reactivity

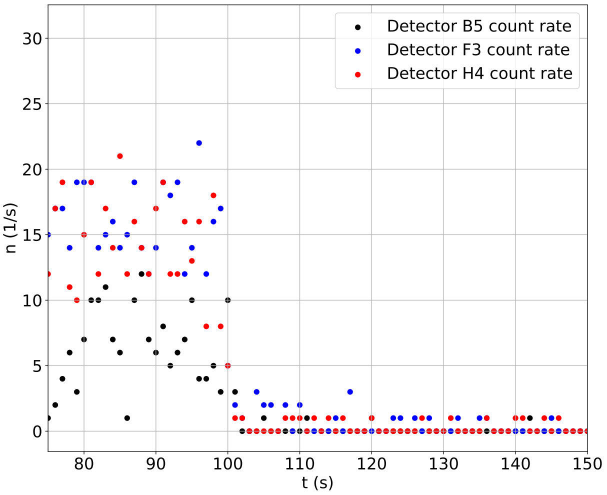

Figure 7. Boron detector count rate at position V with AmBe source [4].

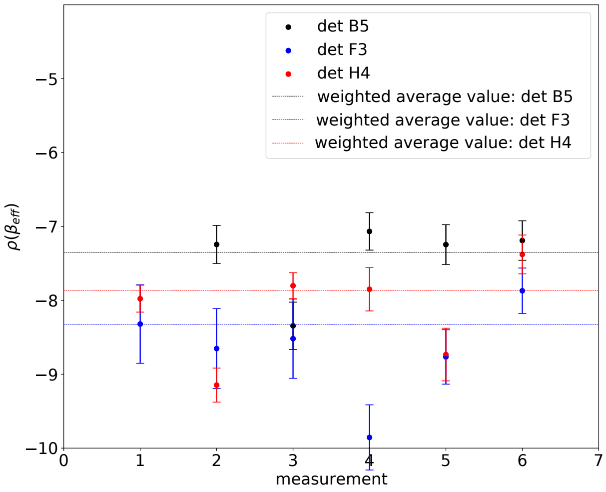

Figure 9. Reactivities obtained from boron detectors using the AmBe source – time step 1 s [4].

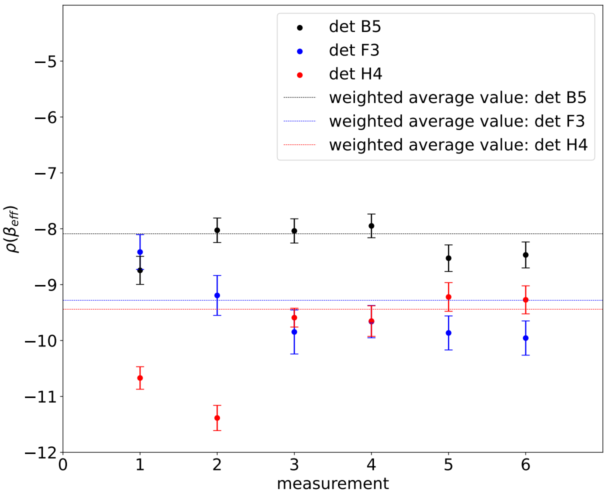

Figure 8. Reactivities obtained from boron detectors using the D-D generator – time step 1 s [4].

$\rho(\beta_{\text{eff}})$ − **time step 1 s**		
	Neutron generator	**AmBe source**
det B5	-8.09 ± 0.06	-7.35 ± 0.12
det F3	-9.28 ± 0.10	-8.33 ± 0.17
det H4	-9.44 ± 0.07	-7.87 ± 0.09
Serpent	**-10.84 ± 10^{-2}**	

Table 1. Weighted average values of reactivity from boron detectors.

calculated using the Serpent 2 code. The calculated reactivity of the VR-1 reactor in the shutdown mode for the C18 core configuration was -10.84 β_{eff}.

Time step 1 s: The results revealed that time optimisation of the neutron detection time step plays a crucial role in the Source-Jerk method and can significantly affect the results.

As shown in Figures 8 and 9, a time step of 1 s resulted in random deviations in reactivity. This error was caused by an insufficient determination of the neutron source removal time. More specificallly, it takes several microseconds for the neutron generator to turn off and roughly 0.7 seconds for the AmBe source to be removed. Since the measurement time step of the detectors is 1 s, the source removal could occur at any point within this one-second interval. Consequently, the integral in Equation (2) varied significantly for each measurement. Furthermore, the exponential drop in the count rate was significant right from the beginning, resulting in differences of more than 1.5 β_{eff}. The weighted average values of reactivity are listed in Table 1.

To address this issue, the measurement time step was reduced to 0.1 s. Although the observational error slightly increased, the reactivity values became significantly more consistent.

In the case of the 1 s time step, both boron detectors and fission chambers (PMV detectors) showed similar results. However, the count rate was lower for the PMV detectors.

Time step 100 ms: By reducing the measurement time step, it was possible to determine the time of removal much more precisely, leading to stable reactivity values. However, as expected, the observational error increased. With the count rate being roughly 10 times lower, the data obtained from the PMV detectors were unusable. The reactivity values measured with two different neutron sources using boron detectors are illustrated in Figures 10, 11, 12, and 13, weighted values of reactivity from the boron detectors are included in Table 2 and the calculated subcriticality is described in Table 3. The comparison of both sources will be discussed in the following section.

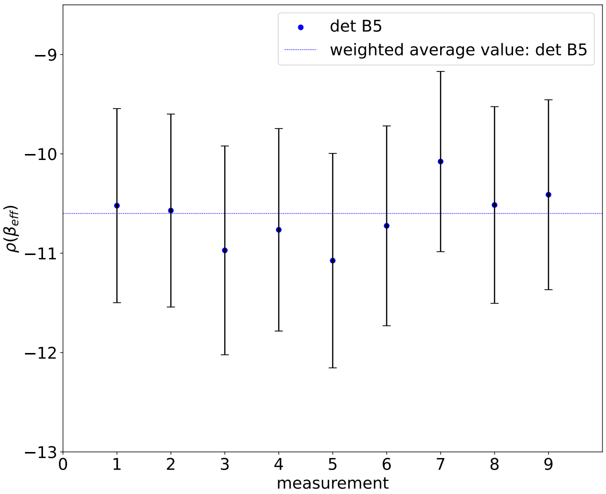

FIGURE 10. Reactivities obtained from boron detector B5 & D-D generator – time step 0.1 s [4].

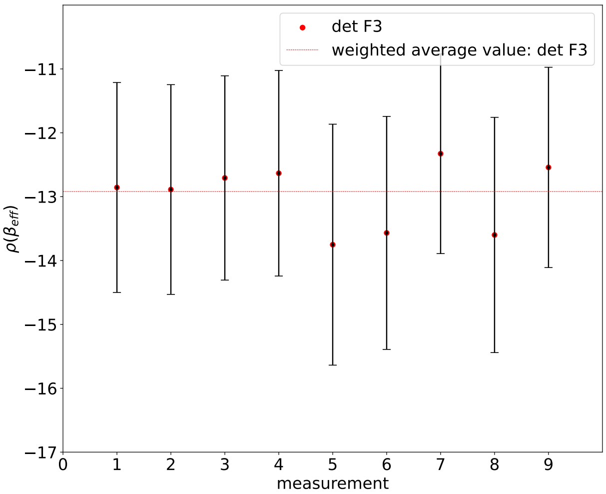

FIGURE 11. Reactivities obtained from boron detector F3 & D-D generator – time step 0.1 s [4].

	$\rho(\beta_{\text{eff}})$ – time step 100 ms	
	Neutron generator	**AmBe source**
det B5	-10.60 ± 0.33	-8.25 ± 0.32
det F3	-12.92 ± 0.56	-8.55 ± 0.51
det H4	-10.56 ± 0.19	—
Serpent	**-10.84** ± **10^{-2}**	

TABLE 2. Weighted average values of reactivity from boron detectors.

3. SERPENT MODEL

In order to compare the results of the experiment carried out on the VR-1 reactor, a complete 3D model of the reactor was created in the stochastic calculation code Serpent [7], version 2.1.32. The ENDF/B-VIII.0 nuclear data library was used to calculate the criticality of the core and the JEFF-3.3 library was used to calculate the kinetic parameters. The Serpent model of the VR-1 reactor is described in detail and validated in papers [8, 9]. This model was adjusted on the basis of the real geometry during the experiment with other neutron sources.

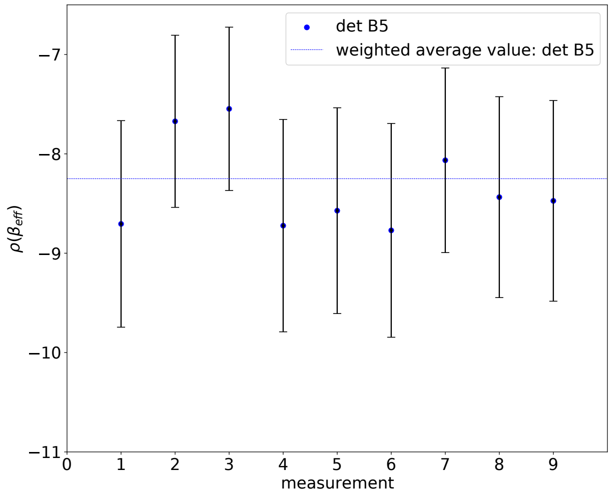

FIGURE 12. Reactivities obtained from boron detector B5 & AmBe source – time step 0.1 s [4].

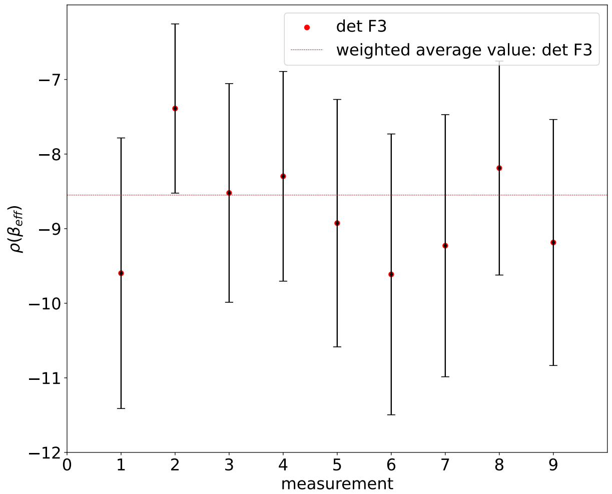

FIGURE 13. Reactivities obtained from boron detector F3 & AmBe source – time step 0.1 s [4].

Radial channel	**Close**	**Open**
k_{eff} [–]	0.9295 ± $1\cdot 10^{-4}$	0.9228 ± $1\cdot 10^{-4}$
ρ [pcm]	-7585 ± 4	-8371 ± 4
ρ [β_{eff}]	**-9.85** ± e^{-2}	**-10.84** ± e^{-2}

TABLE 3. Subcriticality of the VR-1 reactor calculated using the Serpent code.

The following models were created for both calculations (criticality and core kinetics):

- Model with closed radial channel (reference model).
- Model with an open radial channel.
- Model with an open radial channel, AmBe neutron source close to the core.
- Model with an open radial channel filled by the

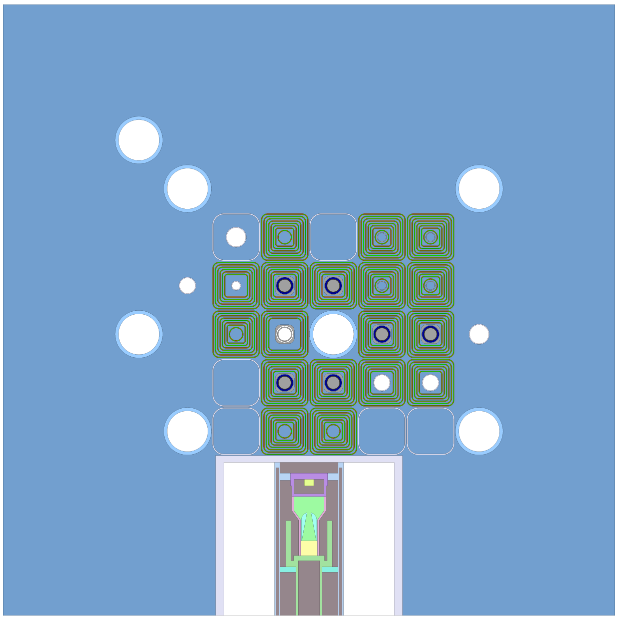

Figure 14. Visualisation of the external D-D neutron generator in the radial channel.

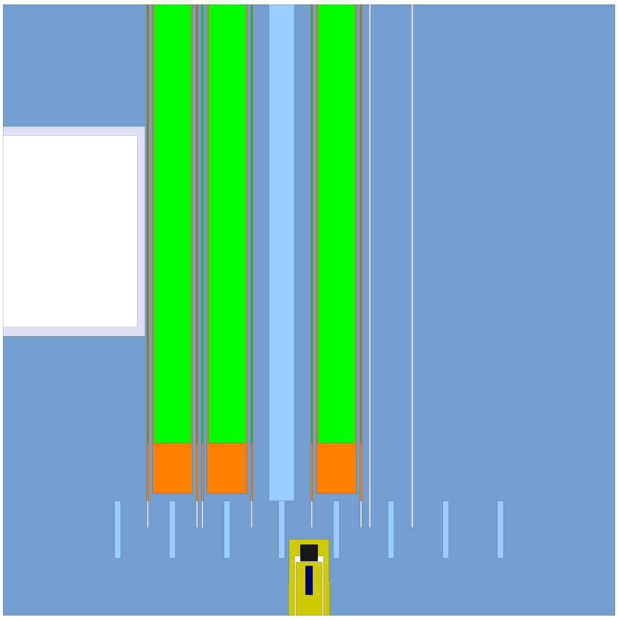

Figure 15. Visualization of the external AmBe neutron source (the YZ direction, X position is 0.5 cm).

D-D neutron generator.

The open radial channel refers to a channel without inserted water plugs and shielding. In the provided simulation, the influence of neutron detectors within the vertical channels, including both the boron detectors and fission chamber detectors for operational power measurement, was not taken into account. Despite this simplification, the impact on the obtained results remains negligible. In addition, the precise geometry of these detectors remains unknown. For a visual reference, Figure 14 displays the illustration of the VR-1 reactor with the external D-D neutron generator.

The model with AmBe neutron source is visualised in the YZ direction in Figure 15. The X position is 0.5 cm to see the axial position of the neutron source, fuel assemblies, and radial channel.

Serpent as a stochastic code requires the definition of the simulated particles. For the calculation of kinetic parameters without external neutron sources, the serpent pop card was used. The parameters of the pop card were 100 000 simulated neutrons, 2 000 active cycles, and 200 inactive cycles for source stabilisation. Criticality calculations were performed with 1 000 000 simulated neutrons, 1 500 active cycles, and 40 inactive cycles. In the case of the external neutron source calculation, the nps card was used with 10^9 simulated neutrons.

In the absence of an external neutron source, the energy spectra within the core are mainly given by the fission reaction and the fuel/moderator fraction. When the D-D neutron generator is present in the radial channel, the energy spectra are primarily governed by the neutrons coming from the generator, specifically at an energy of 2.4 MeV. The energy distribution of the AmBe neutron source is represented through histogram energy bins, according to the ISO standard [10]. Figure 16 shows the visualization of the AmBe energy spectra.

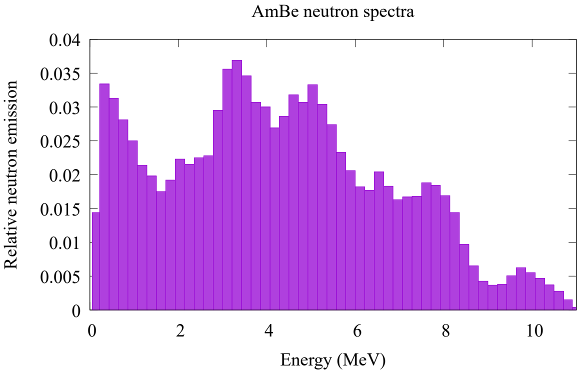

Figure 16. AmBe neutron spectra based on the ISO standard [10].

The subcriticality of the reactor in the shutdown mode is given in Table 3 and the kinetic parameters are given in Table 4. The thermal neutron flux distribution for the neutron generator and the AmBe source is shown in Figures 17 and 18.

4. Results

The experiment revealed several interesting facts about the applicability of the Source-Jerk method using a neutron generator.

Firstly, the D-D generator was capable of providing a much higher count rate compared to the radionuclide AmBe source. This can lead to a lower observational error. However, it is crucial to consider the detector dead time.

Group	β_{eff}	λ_i
1	$2.70183e^{-4} \pm 1.89100e^{-6}$	$1.24667e^{-2} \pm 0.00000$
2	$1.18180e^{-3} \pm 3.78200e^{-6}$	$2.82917e^{-2} \pm 0.00000$
3	$7.50609e^{-4} \pm 3.00200e^{-6}$	$4.25244e^{-2} \pm 0.00000$
4	$1.56508e^{-3} \pm 4.38200e^{-6}$	$1.33042e^{-1} \pm 0.00000$
5	$2.59736e^{-3} \pm 5.71400e^{-6}$	$2.92467e^{-1} \pm 0.00000$
6	$7.36615e^{-4} \pm 2.94600e^{-6}$	$6.66488e^{-1} \pm 0.00000$
7	$6.54765e^{-4} \pm 2.75000e^{-6}$	1.63478 ± 00000
8	$1.90750e^{-4} \pm 1.54500e^{-6}$	3.55460 ± 00000
	Λ	$5.00163e^{-5} \pm 3.00100e^{-8}$
	β_{eff}	$7.94716e^{-3} \pm 9.53700e^{-6}$
	$\sum_{i=1}^{8} \frac{\beta_{\mathrm{eff},i}}{\lambda_i \cdot \beta_{\mathrm{eff}}}$	$1.2998e^{1} \pm 3.15140e^{-2}$

Table 4. Kinetic parameters of the VR-1 reactor – open radial channel.

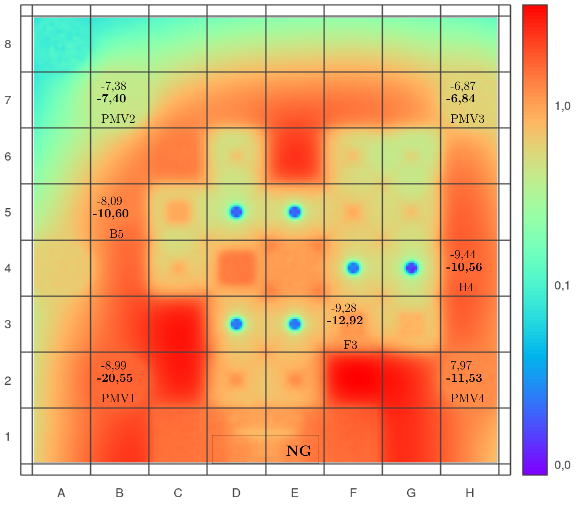

Figure 17. Neutron flux distribution & reactivities – D-D generator.

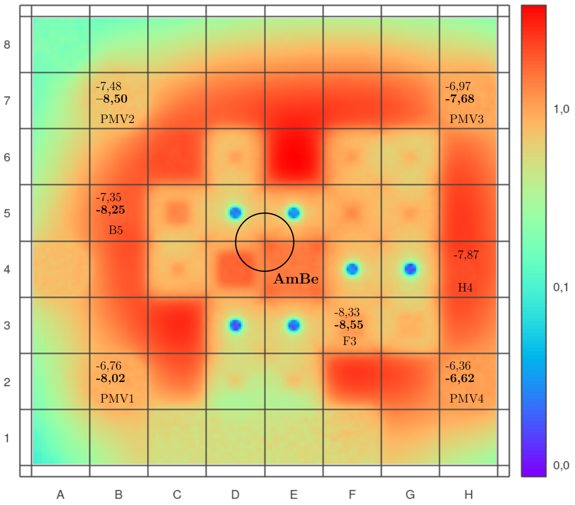

Figure 18. Neutron flux distribution & reactivities – AmBe source.

Another important aspect that has already been discussed in the previous section is the insufficient determination of the source removal time. This inability to determine the exact time of removal originated from the long measurement time step. In the case of the neutron generator, shortening the time step resulted in better and more consistent results, as the removal time was easily distinguishable. However, for the AmBe radionuclide source, it takes more than half a second for the source to be removed, making the improvement less significant due to the unclear decrease in the count rate.

Furthermore, Figures 17 and 18 show the strong spatial dependence observed when using the neutron generator compared to the AmBe source. These figures illustrate the spatial dependence by comparing the thermal neutron flux distribution in the core calculated via Serpent with the measured $\rho(\beta_{\mathrm{eff}})$.

This uneven neutron flux distribution is primarily caused by the position of the neutron source. While the AmBe neutron source is centered under the reactor vessel, the neutron generator is placed in the radial channel from the side of the reactor. This results in an uneven neutron flux distribution, which affects the measured reactivity depending on the position of the detector.

Ultimately, the use of the AmBe radionuclide as a neutron source caused an overestimation of the integral $\int_0^\infty n(t)\mathrm{d}t$, leading to higher measured reactivity values. This overestimation is, again, due to the source removal time. When the AmBe source is removed, it takes about 0.7 seconds for the source to return to the shielding box while it is still emitting neutrons. These emitted neutrons contribute to the integral evaluation and cause an overestimation of the detector count after the source removal. In comparison, the average time for the neutron generator to turn off is a few microseconds. This highlights that the source removal time should be insignificant compared to the measurement time step.

5. Conclusions

The set of spatially independent kinetic equations (see, e.g., [6]) may introduce variations in the obtained reactivity values compared to the actual subcriticality. As a result, further investigations are needed to refine and modify the Source-Jerk method, taking into account the position of the detectors.

In addition to the spatial dependence mentioned above, the concentration of the parent nuclei of the delayed neutrons, as well as the kinetic parameters λ_i and $\beta_{\mathrm{eff},i}$, have spatial dependence. This may raise the question as to whether incorporating mathematical or computational methods into account for this dependence would make the determination of reactivity more precise.

Moreover, the position of the neutron source relative to the active core and detector plays a significant role. Numerical calculations (see Figures 17 and 18) demonstrate that the placement of the external neutron source greatly affects the thermal flux distribution. This points out the critical importance of achieving a consistent neutron flux distribution in order to obtain accurate results from individual detectors.

This study highlights several recommendations for further experimental work with the Source-Jerk method. Firstly, the neutrons emitted by the source should pass through the fuel and reach the detectors at a suitable distance, ensuring a sufficient detector count rate. Moreover, it is crucial to place the source in such a manner that it uniformly affects the entire core. Finally, great attention should be paid when selecting the appropriate time step for data collection and analysis.

Addressing these recommendations and refining the methodology for reactivity measurements using the Source-Jerk method will contribute to enhancing the accuracy and reliability of reactor safety assessments and optimisation efforts in VR-1. This work will also provide a basis for more in-depth studies of the spatial dependence of the Source-Jerk method and for a development of pulsed reactivity measurement methods on the VR-2 reactor. Both of these studies will share the same experimental charateristics and some of the presented conclusions may be generalised.

Acknowledgements

The experimental work described in the paper was supported by the project "Modernization of the Large Research Infrastructure VR-1 – Training Reactor for Research Activities" (reg. nr. CZ.02.1.01/0.0/0.0/ 18_046/0015833) supported by Operational Programme Research, Development and Education co-financed from European Structural and Investment Funds and from state budget of the Czech Republic.

References

[1] G. Spriggs, R. A. Pederson. Source-jerk analysis using a semi-explicit inverse kinetic technique. *Presented at the DOE Subcritical Reactivity Measurements Workshop* 1985. `https://digital.library.unt.edu/ark:/67531/metadc1056620/m2/1/high_res_d/5147458.pdf`

[2] T. Gozani. *Subcritical reactor kinetics and reactivity measurements*. Ph.D. thesis, ETH Zurich, 1962. `https://doi.org/10.3929/ethz-a-000087577`

[3] J. Rataj, F. Fejt, J. Frýbort, et al. The project of VR-2 subcritical assembly. *Nuclear Engineering and Design* **386**:111578, 2022. `https://doi.org/10.1016/j.nucengdes.2021.111578`

[4] J. Mátl. Application of the source-jerk method using a neutron generator at VR-1 reactor. In *Proceedings of the European Nuclear Young Generation Forum*, pp. 192–195. Kraków, PL. `https://enygf.org/new/ENYGF2023%20Book%20of%20Proceedings.pdf?_t=1690963680`.

[5] L. Frybortova, J. Rataj, L. Sklenka, et al. The training reactor VR-1 – 30 years of operation. In *2020 21st International Scientific Conference on Electric Power Engineering (EPE)*, pp. 1–7. IEEE, 2020. `https://doi.org/10.1109/EPE51172.2020.9269254`

[6] T. Bílý, J. Rataj, O. Huml, O. Chvála. Effect of kinetics parameters on transients calculations in external source driven subcritical VR-1 reactor. *Annals of Nuclear Energy* **123**:97–109, 2019. `https://doi.org/10.1016/j.anucene.2018.09.007`

[7] J. Leppänen, et al. Serpent – a continuous-energy Monte Carlo reactor physics burnup calculation code. *VTT Technical Research Centre of Finland* **4**:455, 2013. [2023-09-18], `http://montecarlo.vtt.fi/download/Serpent_manual.pdf`.

[8] F. Fejt, P. Suk, J. Frybort, J. Rataj. Utilization of PARCS/Serpent in small-scale reactor – multiplication factor, rod worth, and transient. *Annals of Nuclear Energy* **166**:108757, 2022. `https://doi.org/10.1016/j.anucene.2021.108757`

[9] O. Novak, L. Sklenka. New scram experimental device at training reactor VR-1. *EPJ Web of Conferences* **247**:08008, 2021. `https://doi.org/10.1051/epjconf/202124708008`

[10] International Standard ISO 8529. Neutron reference radiations for calibrating neutron-measuring devices used for radiation protection purposes and for determining their response as a function of neutron energy. *ISO/TC 85/SC 2 Radiological protection* 1989.