American Journal of Science, Engineering and Technology
2023; 8(2): 104-109
http://www.sciencepublishinggroup.com/j/ajset
doi: 10.11648/j.ajset.20230802.14
ISSN: 2578-8345 (Print); ISSN: 2578-8353 (Online)

Comparative Study of Transfer Functions for NRAD and AGN-201 Reactor Systems

Harish Aryal

Mechanical Engineering, Marymount University, Arlington, The United States

Email address:
haryal@marymount.edu

To cite this article:
Harish Aryal. Comparative Study of Transfer Functions for NRAD and AGN-201 Reactor Systems. *American Journal of Science, Engineering and Technology*. Vol. 8, No. 2, 2023, pp. 104-109. doi: 10.11648/j.ajset.20230802.14

Received: April 16, 2023; **Accepted**: May 22, 2023; **Published**: May 31, 2023

Abstract: The project is about building an infrastructure for an open loop technique and implementing this technique to measure the reactivity worth of small samples. The reactivity samples are allowed to oscillate back and forth in the reactor system to cause perturbations and the corresponding reactor response is measured in the form of the transfer function. The transfer function obtained is used to determine stability characteristics along with other kinetic parameters such as delayed neutron fraction, prompt neutron lifetime, shutdown margins, and absolute power**.** This paper compares transfer functions for reactors like Neutron Radiography (NRAD) and Aerojet General Nuclear (AGN-201). The magnitude of the transfer function correlates with the reactivity of the sample that caused the perturbation. In addition, the transfer function allows one to determine whether the reactor is a stable system or not. In other words, the reactor's response to the change in neutron population in the reactor can be easily described. Moreover, a transfer function measurement is useful to extract important kinetic parameters of the reactor system, such as instance prompt neutron generation lifetime, reactivity shutdown margin, absolute power, etc. The transfer function plots presented in the results section correlate the reactivity of the sample that caused perturbations. NRAD was found to have a higher break frequency than that AGN-201. This was an expected result since break frequency is inversely proportional to neutron generation time. With this relation, break frequency was found to be around 306 Hertz. So, the reactor cannot respond beyond this frequency but passes the low frequencies. The corresponding analysis and comparative transfer function plots using MATLAB for these two reactor systems are presented in the results section. Many reactivity measurements have been already in practice however if the transfer function technique can give reactivity measurements with similar or better precision and accuracy, it could be a great benefit. Moreover, this can be installed in those facilities where more complex systems cannot be incorporated easily.

Keywords: Transfer Function, Radiograph, Reactivity, Shutdown, NRAD, AGN-201

1. Introduction

1.1. Reactor Transfer Function

With a proper understanding of the transfer function, any instantaneous state of the core can be promptly corrected for safety to avoid further damage that can lead to failures with the potential for radioactive releases via mechanical and local overheating phenomena [19]. Similar experiments deal with the analysis of reactor neutron noise, and numerical simulations that reproduce the response of the system to the perturbations are often mandatory to solve the inverse problem, allowing the identification of the source of noise (e.g., a faulty fuel rod or fuel assembly) from a collection of measured signals [1, 8]. George Imel and his research team performed a similar experiment using an open loop where the reactivity is perturbed, and the reactor power is allowed to follow the perturbation. An analysis of the resulting time-dependent power allows the reactivity to be inferred via inverse kinetics [9, 19, 20-22]. Another motivation for transfer function research is that it allows retrieving of information about the perturbations from the neutron flux measurements via an inversion algorithm, which can be based on advanced signal processing techniques or machine learning [19]. In their study, the reactor transfer function was modeled using the neutron transport equation, while the possible perturbations are expressed in terms of changes in the macroscopic nuclear cross-sections. Another avenue of research is based on an adaptive control mechanism that is designed to estimate the unknown upper bound of a lumped uncertain term that is composed of lumped disturbances and system states in real-time. The estimated values are then added to the controller, resulting in the control system being capable of compensating for the adverse effects of the lumped disturbances efficiently in real-time [11]. However, this method cannot effectively deal with unknown model uncertainties and high-frequency disturbances. Eun-Ki Lee* and his team used Dynamic Control rod Reactivity Measurement (DCRM) method using detector current signals of PWRs to ascertain perturbations however this method is not the best option while using low-sensitivity fission chambers and in some cases where there is a non-linearity-of-mean-square voltage at low power [15].

The output (power) of any physical system (reactor) to a signal input (reactivity) applied to it can be studied with the help of the transfer function $H(s)$,

Mathematically,

$$H(s) = \frac{Laplace\ transform\ of\ the\ response\ (output)}{Laplace\ transform\ of\ input} \quad (1)$$

The block diagram with time and frequency domain can be found in Figure 1 below:

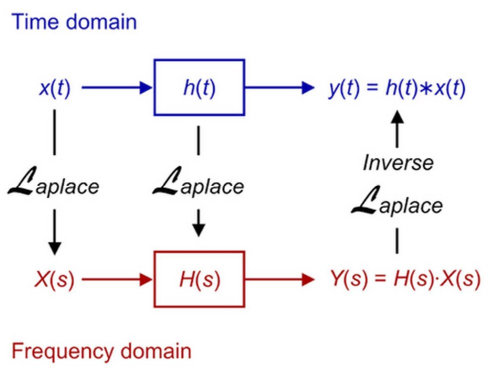

Figure 1. *Transfer Function in Two Domains [5].*

Depending on whether the output affects the input or not, the transfer function can be divided into open loop transfer function and closed loop transfer function. The following section explains those methods of determining transfer functions in detail.

1.2. Kinetics and Inverse Kinetics

Before beginning, a few assumptions were made. Initially, the reactor is assumed to be in a steady state where all the time derivatives are zero. We assume the point kinetic model is valid for small fluctuations in the equilibrium power, and we assume a small oscillation in reactivity, power, etc. about the equilibrium value. For such oscillations, average values can be assumed to be the same as the equilibrium values which is not always true in case of the large amplitude oscillations [10]. Moreover, for such small oscillations, all the higher-order perturbations could be easily ignored (linearization). However, to design a robust and safe system, this may not be the ideal assumption [13].

Before beginning, a few assumptions were made. Initially, the reactor is assumed to be in a steady state where all the time derivatives are zero. We assume the point kinetic model is valid for small fluctuations in the equilibrium power, and we assume a small oscillation in reactivity, power, etc. about the equilibrium value. For such oscillations, average values can be assumed to be the same as the equilibrium values which is not always true in case of the large amplitude oscillations [10]. Moreover, for such small oscillations, all the higher-order perturbations could be easily ignored (linearization). The transfer function equation is given as equation 2 below:

$$G(s) = \frac{N_0}{\Lambda s + \beta - \rho_0 - \sum_{i=1}^{6} \frac{\lambda_i \beta_i}{(s+\lambda_i)}} \quad (2)$$

Where G(s) is the amplitude of response, ρ is the reactivity, β is the delayed neutron fraction, t is the time in seconds, λ_i is the decay constant of the ith group with the units of sec^{-1}, β_i is the delayed neutron fraction (fraction of the delayed neutrons from group "i" to total number of neutrons), Λ is the generation time, n(t)is the neutron density at any time and N0 is the initial neutron density at t=0 sec.

To determine the reactivity of the given sample at a specified power level, the open loop technique uses inverse kinetics. Inverse kinetics helps determine the time dependence of the applied reactivity deduced from specific power variation. Moreover, the interpretation of the power responses provides information about the feedback mechanisms in the reactor [7]. The governing equation to calculate the reactivity is as follows [16].

1.3. Reactor Description

Two different reactors were studied. The Aerojet

General Nuclear -201 (AGN-201) reactor is in the basement of the Lilibridge Engineering Building at Idaho State University. It is a low-power reactor (licensed to 5W) primarily used for research and teaching purposes. It consists of uranium dioxide (UO_2) as the fissile fuel homogeneously mixed with polyethylene. For the research purpose, the reactor has five experimental ports to allow the insertion of the materials in the core: four beam ports running north to south and a glory hole running east to west through the center of the core [16]. Figure 2 below shows the broad view of the reactor.

NRAD:

The Neutron Radiography (NRAD) reactor is in the basement of the Hot Fuels Examination Facility (HFEF) at the Materials and Fuels Complex at the Idaho National Laboratory (INL). It is a 250kW TRIGA reactor with a rectangular grid-style core used for conducting neutron radiography and performing specimen activation experiments. The reactor is inside a rectangular concrete confinement room located 120 feet from the control room. The reactor room is accessed by opening two shielded doors that seal off the room while the reactor is operating. The reactor is covered by an additional shielded platform of which half is stationary and half slides on rollers to access the core (see Figure 3). The reactor core is covered by water. The reactor room is approximately 10 feet deep, 12 feet wide, and 17 feet in length, but it only has 5.5 feet of overhead clearance space for workers. This area also contains most of the pumping systems and additional electronic equipment that regulates the reactor, as shown in Figure 3 below.

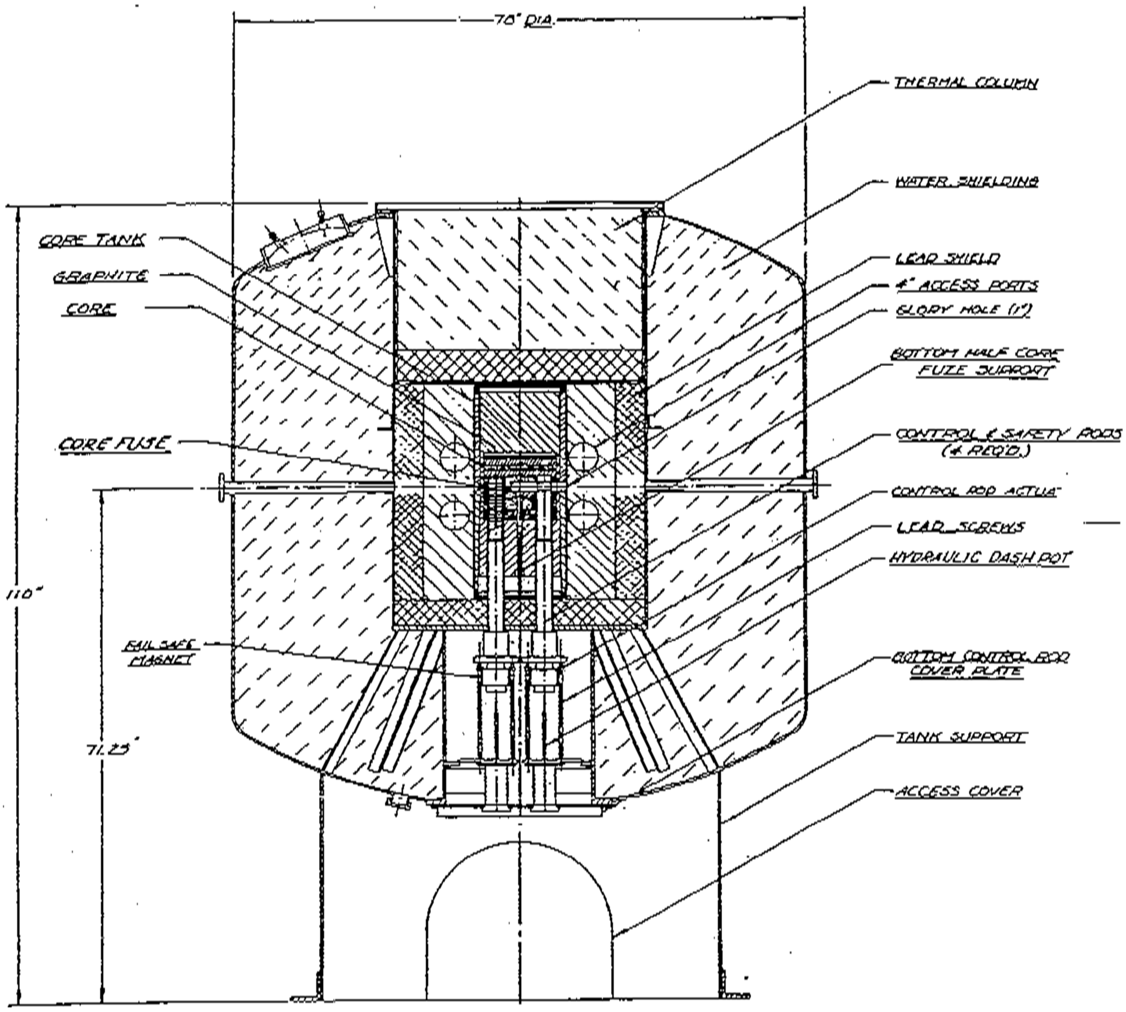

Figure 2. *Broad View of the AGN-201 Reactor [5].*

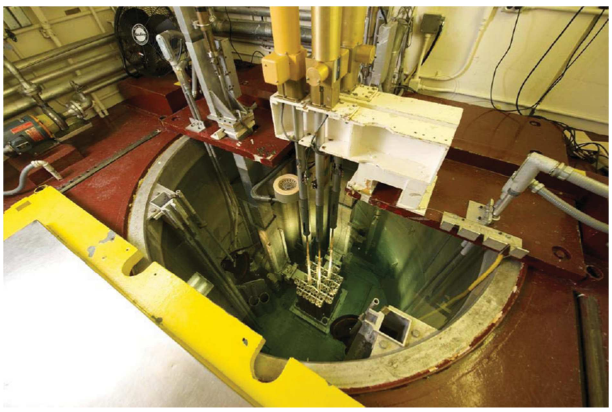

Figure 3. *Reactor Design [7].*

There are numerous design restraints that need to be considered before a system can be effectively and wisely chosen. One constraint imposed on this oscillator design problem is that only a very small amount of excess reactivity is available (50 cents). Thus, the solution cannot involve anything that will significantly lower the reactivity (e.g., air voids) and cause the reactor to become subcritical or have any transient conditions [14]. Another constraint governing the scope of this problem is the amount of foundation space available near the core support assembly of the reactor core. The system must be able to fit in the space available.

2. Materials and Methods

Idaho State University's AGN-201 reactor was used for most of the oscillator experiments. AGN 201 is a low-power research reactor that consists of a polyethylene core with uranium dioxide (U02) grains homogeneously mixed throughout the polyethylene. The core is then surrounded by a graphite reflector, a lead shield, a water shield, and the outer steel tank. The reactor has five experimental ports to allow for the insertion of materials near the core: four experimental beam ports running north to south through the graphite reflector just outside the core region and one port running east to west through the center of the core (known as the glory hole) [17]. The high-speed linear actuator has guide rails and is driven by a motor that is mounted on the carriage that runs on the track. The actuators can achieve a linear velocity of 60 cm /s over a range of 20 cm. The frequency of oscillation can reach 3 Hz. These actuators are designed to oscillate samples back and forth to generate necessary perturbations. Corresponding power data are recorded that correlate the position of the samples. A set of neutron detectors are installed at the edge of the reactor for detection and that provides neutron flux [6]. While the currents measured are in the order of picoamps are amplified using preamplifiers and amplifiers and are sent to the data acquisition system. Necessary calculations to generate transfer function are processed in MATLAB and the corresponding plots are presented in the result section.

Before measuring the transfer functions and reactivity changes, kinetics parameters need to be ascertained. The parameters obtained are as follows [7].

Effective delayed neutron fraction (β_{eff}) = 0.0075

Neutron generation time = 24.5 microseconds

The decay constants of the precursor groups and the relative yields are given in table below [12].

Table 1. *Delayed Neutron Yield and Half-Life Data for U-235.*

Group	T1/2(sec)	Relative Yield
1	54.51	0.038+/-0.004
2	21.84	0.213+/-0.007
3	6.00	0.188+/-0.024
4	2.23	0.407+/-0.010
5	0.496	0.128+/-0.012
6	0.179	0.026+/-0.004

The parameters were found to be of the same order of magnitude as those used in the ISU AGN-201. Using the NRAD parameters, a transfer function plot was obtained using MATLAB. This plot was then compared with that obtained using the AGN-201 parameters. These plots can be found in the results section.

3. Results

Figure 4 below shows the transfer function plot comparing NRAD data with AGN-201 data. These plots were obtained by using MATLAB with the provided neutron parameters. A comparison of the transfer functions as seen in the plot below showed the feasibility and applicability of this technique to measure the reactivity of small samples. NRAD was found to have a higher break frequency as compared to AGN-201.

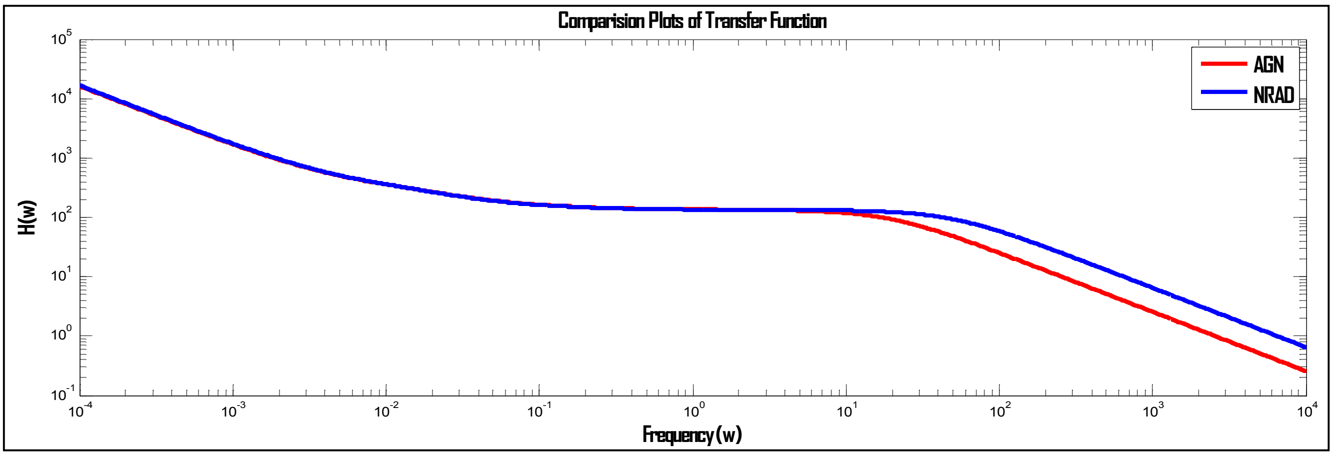

Figure 4. *Comparison Plots of Transfer Function of AGN-201 and NRAD.*

4. Conclusion

The transfer function plots presented in the results section correlate the reactivity of the sample that caused perturbations. NRAD was found to have a higher break frequency than that AGN-201. This was an expected result since break frequency is inversely proportional to neutron generation time ($f_{break} = \frac{\beta}{\Lambda}$). With this relation, break frequency was found to be around 306 Hertz. So, the reactor cannot respond beyond this frequency but passes the low frequencies. Similar behavior of NRAD and AGN-201 at low frequencies adds confidence in implementing the open loop technique to measure the reactivity worth of small samples. This research may serve as a starting point for future research in measuring reactivity responses due to possible perturbations. Similar experimental tools may be used for both reactor systems since they have similar behavior as depicted by transfer function plots.

5. Discussion

There were a few limitations in determining the reactivity of small-worth samples. The most important limitation is the reactor noise. Reactor noise is defined as the inherent fluctuation in neutron level due to the statistical distribution of fission neutrons. The origin of such fluctuations might be either mechanical or neutronic. Mechanical variations are caused by the movement of the control rods, coolant flow across the channels, natural vibration of the system, etc. In zero-power reactors, mechanical contribution to the reactor noise is negligible On the other hand, neutronic fluctuations are caused due to the discrete nature of fission, capture, and leakage. A theoretical reactivity limit for reactivity measurement was calculated using the equation below [16]. For example, the variance of a U-235 fueled reactor such as NRAD is given as:

$$\sigma(t) = \frac{5.1}{\sqrt{Wt}} \times 10^{-6} \frac{\Delta k}{k} \quad (3)$$

Where, W is the reactor power in watts, t is the time of measurement in seconds and k is the multiplication factor. Equation 1 gives the minimum uncertainty that could be achieved from a reactor. It can be seen from equation 1 that uncertainty depends on two factors, t and W. Time of measurement could be shortened by operating at higher power but at higher power feedback effects such as temperature will interfere. Thus, a proper selection of time and power is crucial. For instance, if NRAD is operated at a power of 50 watt for 100 second, $\sigma(t)$ can be calculated as follows: [4, 5]

$$\sigma(t) = \frac{5.1}{\sqrt{50 \times 100}} \times 10^{-6} \frac{\Delta k}{k} = 7.21 \times 10^{-8} \frac{\Delta k}{k} = 0.00096\ cents \quad (4)$$

Other design constraints that should be considered before installing an open loop in NRAD are the lack of available space and limited excess reactivity (50 cents). Proper material selection for the tube, location of oscillator tube insertion, and detection method were studied for the design which can be found in the later chapters. One of the drawbacks of this oscillation technique is that it requires that the reactor must be externally perturbed during the experiment and online computation is complicated in some cases. Another limitation is not considering harmonics. Any vibrating fuel pin introduces noise sources at the frequency of vibrations, as well as at higher harmonics, the first one being the most significant of those [2]. Depending on the harmonics considered, the position of the vibrating fuel pin, the size of the core and its macroscopic cross-sections, different noise responses should have been studied [18].

Further work is necessary to validate these findings in more complicated geometry such as Advanced Test Reactor (ATR) to seek validity. However, this method could be the starting point to start measuring reactivity worth in simpler reactors such as AGN-201 and NRAD that has similar transfer function plots as presented in the result above. If we can adopt this model in different types of nuclear reactors in general, it serves as a possible pathway for future research and development. In future, a comprehensive uncertainty analysis methodology with sensitivity analysis will be developed for modeling stationary neutron flux oscillations induced by fuel rods vibrations and other induced noises in a zero-power reactor [3].

References

[1] Ahmad, S., Abdulraheem, K. K., Tolokonsky, A. O., & Ahmed, H. (2023). Active disturbance rejection control of pressurized water reactor. Annals of Nuclear Energy, 189. https://doi.org/10.1016/j.anucene.2023.109845

[2] Ayazuddin, S. K., & Sari, S. A. A. (1984a). REACTOR TRANSFER FUNCTION MEASUREMENT AT PARR BY NEUTRON NOISE ANALYSIS.

[3] Ayazuddin, S. K., & Sari, S. A. A. (1984b). REACTOR TRANSFER FUNCTION MEASUREMENT AT PARR BY NEUTRON NOISE ANALYSIS.

[4] Baker, Benjamin Allen. Reactor Parameters for the ISU-AGN-201 Reactor. Pocatello, Idaho: Idaho State University, 2013.

[5] Baker, Benjamin Allen. Comparison of Open Loop and Closed Loop Reactivity Measurement Technique on the ISU-AGN-201 Reactor. Pocatello, Idaho: Idaho State University, 2013.

[6] Bläsius, C., Herb, J., Sievers, J., Knospe, A., Viebach, M., & Lange, C. (2022). Mechanical model for the motion of RPV internals affecting neutron flux noise. Annals of Nuclear Energy, 176. https://doi.org/10.1016/j.anucene.2022.109243

[7] Bess, John D. et al. FreshCore Reload of the Neutron Radiography (NRAD) Reactor with Uranium (20) –Erbium -Zirconium-Hydride Fuel Department of Energy, Idaho National Laboratory, 2010.

[8] Demazière, C., Rouchon, A., & Zoia, A. (2022). Understanding the neutron noise induced by fuel assembly vibrations in linear theory. Annals of Nuclear Energy, 175. https://doi.org/10.1016/j.anucene.2022.109169

[9] Herb, J., Périn, Y., Yum, S., Mylonakis, A., Demazière, C., Vinai, P., Yu, M., Wingate, J., & Hursin, M. (2022). Sensitivity analysis in core diagnostics. Annals of Nuclear Energy, 178. https://doi.org/10.1016/j.anucene.2022.109350

[10] Hetrick, David L. Dynamics of Nuclear Reactors. La Grange Park, Illinois: American Nuclear Society, 1993.

[11] Hui, J., & Yuan, J. (2022). Adaptive second-order nonsingular terminal sliding mode power-level control for nuclear power plants. Nuclear Engineering and Technology, 54 (5), 1644–1651. https://doi.org/10.1016/j.net.2021.10.041

[12] James J. Duderstadt, Louis J. Hamilton. Nuclear Reactor Analysis. s. l.: John Wiley & Sons, inc., 1976.

[13] Kim, H., & Kim, J. (2023). Long-term prediction of safety parameters with uncertainty estimation in emergency situations at nuclear power plants. Nuclear Engineering and Technology. https://doi.org/10.1016/j.net.2023.01.026

[14] Korbut, T., Kuzmin, A., Rudak, E., & Kravchenko, M. (2021). Transient analysis of a subcritical reactor core with a MOX-Fuel using the birth-and-death model. Nuclear Engineering and Technology, 53 (6), 1731–1735. https://doi.org/10.1016/j.net.2020.11.023

[15] Lee, E. K., Jo, Y. G., & Lee, H. S. (2022). Dynamic rod worth measurement method based on eqilibrium -kinetics status. Nuclear Engineering and Technology, 54 (3), 781–789. https://doi.org/10.1016/j.net.2021.08.033

[16] Riley, Tony. Calibration of Reactivity Oscillator for ISU-AGN-201 Reactor. Pocatello: Idaho State University (Thesis), 2011.

[17] Study of the Open Loop and Closed Loop Oscillator Techniques. (n.d.).

[18] Vidal-Ferràndiz, A., Ginestar, D., Carreño, A., Verdú, G., Dokhane, A., Verma, V., Perin, Y., Herb, J., Mylonakis, A., Demazière, C., & Vinai, P. (2022). Modelling and simulations of reactor neutron noise induced by mechanical vibrations. Annals of Nuclear Energy, 177. https://doi.org/10.1016/j.anucene.2022.109300

[19] Vinai, P., Brighenti, A., Demazière, C., & Gasse, B. (n.d.). Development and comparison of highorder solvers for reactor noise analysis. http://cortex-h2020.eu

[20] Vinai, P., Yi, H., Demazière, C., Rouchon, A., Zoia, A., Vidal-Ferràndiz, A., Carreño, A., Ginestar, D., & Verdú, G. (2023a). On the simulation of neutron noise induced by vibrations of fuel pins in a fuel assembly. Annals of Nuclear Energy, 181. https://doi.org/10.1016/j.anucene.2022.109521

[21] Vinai, P., Yi, H., Demazière, C., Rouchon, A., Zoia, A., Vidal-Ferràndiz, A., Carreño, A., Ginestar, D., & Verdú, G. (2023b). On the simulation of neutron noise induced by vibrations of fuel pins in a fuel assembly. Annals of Nuclear Energy, 181. https://doi.org/10.1016/j.anucene.2022.109521

[22] Yum, S., Hursin, M., Vasiliev, A., Vinai, P., Mylonakis, A. G., Demazière, C., & Macián-Juan, R. (2022). Uncertainty analyses of neutron noise simulations in a Zero-Power reactor. Annals of Nuclear Energy, 174. https://doi.org/10.1016/j.anucene.2022.109157