nucmag.com

atw

International Journal
for Nuclear Power

2020

6/7

Deep Geological Radioactive and Chemical Waste Disposal: Where We Stand and Where We Go

How Final Disposal Can Work

What has Happened to the U.S. Nuclear Waste Disposal Program?

ISSN · 1431-5254
23.55 €

Issue 6/7 | 2020

June/July

Contents

Cover:
Picture alliance | Lehtikuva | Emmi Korhonen

G = German
E/G = English/German

Investigation on PWR Neutron Noise Patterns

Marco Viebach, Carsten Lange and Antonio Hurtado

Planned entry for KERNTECHNIK 2020

1 Introduction Investigation of the unexplained changes of neutron flux fluctuation magnitudes observed in KWU-built PWRs (cf. *[1,2]*) has drawn attention to long known (cf. *[3]*) but still incompletely understood spatial correlation patterns of the neutron flux fluctuations in the frequency range 0–2 Hz (cf. *[4]*). These patterns, namely an out-of-phase behavior of signals from oppositely located core quadrants and an in-phase behavior of signals from axially aligned locations, are the dominant fluctuation phenomena because the range 0–2 Hz carries more than 95 % of the power of the signal fluctuations and the coherence functions of respective signal pairings have values between 0.5 and 1.0 in this frequency range (cf. *[4]*). Therefore, finding the mechanism effecting the measured fluctuation patterns is believed to be key to explain the changes of the fluctuation amplitudes.

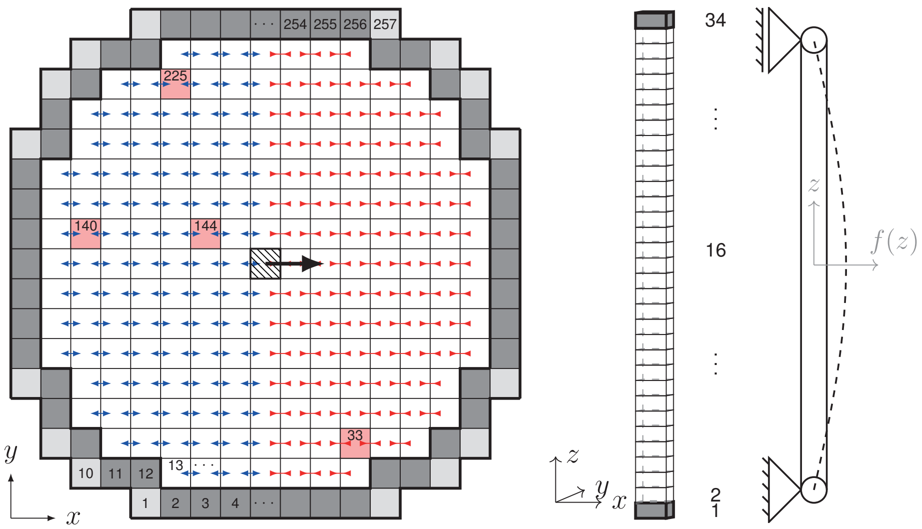
Recent attempts try to understand the patterns as being triggered from a long-range perturbation. Synchronized lateral fuel-assembly vibrations are suggested to provide such kind of perturbation (cf. *[4]*). A synchronous vibration of the entire core (as also proposed in Ref. *[3]*), leading to a perturbation possibly called “reflector effect”, results in signal correlations similar to those of the measurements. But the corresponding magnitudes are found roughly one order of magnitude lower than observed in the measurements (cf. *[5]*).

As a new attempt, synchronized lateral vibrations that do not involve the entire reactor core are suggested as an approach to overcome the shortcoming of a low fluctuation magnitude in the model (cf. *[5]*). Such vibration mode corresponds to a perturbation that is located in regions more central than for the “reflector effect”. Simulations of corresponding scenarios give magnitudes of the neutron flux fluctuations that are within the range of the measured values (i. e. percents) and correlation patterns that qualitatively agree with the measured ones (cf. *[6,7]*).

The work at hand investigates a special case of synchronous lateral fuel-assembly vibration that involves all fuel-assembly rows, though with unequal amplitudes. It is assumed that large-scale coolant flow fluctuations drive the fuel-assembly vibration such that the central fuel assembly has the largest amplitude, both in x- and y-direction. The vibration amplitudes of the surrounding fuel assemblies are lower with the lowest amplitude for the outermost ones. As an extreme case, this assumption is represented by a synchronous fluctuation of all fuel-assembly gaps. This scenario is simulated for a KWU Vor-Konvoi PWR by the neutron-noise tool *CORE SIM* *[8]* in the frequency domain. The model is based on a corresponding input (cf. *[9]*) of the reactor dynamics code *DYN3D* *[10]*. A simulation of similar type for the above-mentioned “reflector effect” is presented in Ref. *[11]*.

The simulation shown here aims at studying the neutron flux fluctuation patterns that are introduced by the described scenario. Furthermore, it investigates whether this scenario may adequately approximate the actual picture in KWU-built PWRs. Therefore, the work at hand tries to broaden the set of potentially relevant perturbation sources that can lead to the observed phenomena. Note that it is not primarily intended to provide quantitative results.

The article is structured as follows. After the introduction, the model is described in detail before outlining the concept of *CORE SIM* and the preparation of its input. Then, the simulation results are shown by means of spatial distributions of absolute values (amplitudes) and phases of the neutron flux fluctuations. After a discussion, the article is closed by drawing conclusions.



(a) Spatial setup. Radial-azimuthal. (b) Spatial setup. Axial. (c) Bow shape.

Fig. 1.
Spatial (nodal) setup (a, b) used for the simulation and illustration of the fuel-assembly bow (c). The reflector regions are filled gray (side with dark and corner with light shading). Channels with detector signals referenced in the results section are shaded red. Numbers $n_{Ch} = 1, 2, \ldots, 257$ denote channel indices (a) and $n_z = 1, 2, \ldots, 34$ axial levels (b), resp. The leading, central fuel assembly is represented hatched. Considering a given instant, expansion arrows ◄► label fuel-assembly gaps that are expanded, and contraction arrows ►◄ label those that are contracted (a). The bow shape is illustrated by a dashed line against the straight, nominal shape (c).

2 Simulation of neutron flux fluctuations

2.1 Models and methods

2.1.1 Modelling of coherent fuel-assembly gap fluctuation

The simulation considers a 4-loop KWU Vor-Konvoi reactor at nominal power at end of cycle. **Figures 1a** and **1b** illustrate the spatial (nodal) setup for the neutron-kinetics part and the thermal-hydraulics part of the simulation. The steady-state system is perturbed by the vibration of the fuel assemblies. The perturbation enters the calculation via time-dependent variations of the group constants of the neutron-kinetics part (cf. Sec. 2.1.3). For simplicity, the vibration $w_n(z, t)$ of the n^{th} fuel assembly ($n = 1, 2, \ldots, 193$) is considered only in x-direction. It is approximated by a sinusoidal axial shape function $f(z) = \sin(\pi z/L)$ (cf. **1c**), with L representing the axial fuel-assembly length, and a time-dependent elongation $A_n(t)$, i. e. $w_n(z, t) = f(z)A_n(t)$.

The scenario studied here assumes that all fuel assemblies vibrate synchronously, but their elongations $A_n(t)$ have unequal magnitude with the central one having the largest. The scenario is motivated by the idea that in the central core region, the fluctuations of the coolant flows of each of the four loops act on the fuel assemblies there, leading to correspondingly large vibration magnitudes. The outer fuel assemblies are less affected, responding with smaller magnitudes. For simplicity, it is assumed that the magnitude linearly decreases with increasing distance from the core center. At the outer fuel-assembly row, the magnitude is zero. This assumption leads to uniform fluctuations of all fuel-assembly gaps. The situation is illustrated in **Figure 1c**. For each fuel assembly n, the variations of the center-to-center distances d_{nj_n} to its four adjacent fuel assemblies $j_n \in$ {north, south, east, west} are averaged forming an effective fuel-assembly pitch variation

$$p_n(z,t) := \frac{1}{4} \cdot \sum_{j_n \in \{\text{north,south,east,west}\}} d_{nj_n}(z,t)\,. \tag{1}$$

2.1.2 Calculation of neutron flux fluctuations with *CORE SIM*

The code *CORE SIM* solves the neutron transport equation using diffusion theory, two energy groups, and one group of delayed neutrons *[8]*,

$$\begin{aligned}\frac{1}{v_1}\frac{\partial}{\partial t}\phi_1(\boldsymbol{r},t) \;=\;& \nabla(D_{1,0}(\boldsymbol{r})\nabla\phi_1(\boldsymbol{r},t)) \\ &+((1-\beta)\nu\Sigma_{\text{f},1}(\boldsymbol{r},t)-\Sigma_{\text{a},1}(\boldsymbol{r},t)-\Sigma_{\text{r}}(\boldsymbol{r},t))\,\phi_1(\boldsymbol{r},t) \\ &+(1-\beta)\nu\Sigma_{\text{f},2}(\boldsymbol{r},t)\,\phi_2(\boldsymbol{r},t)+\lambda C(\boldsymbol{r},t)+S_1(\boldsymbol{r},t)\,,\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{1}{v_2}\frac{\partial}{\partial t}\phi_2(\boldsymbol{r},t) \;=\;& \nabla(D_{2,0}(\boldsymbol{r})\nabla\phi_2(\boldsymbol{r},t)) \\ &+\Sigma_{\text{r}}(\boldsymbol{r},t)\,\phi_1(\boldsymbol{r},t)-\Sigma_{\text{a},2}(\boldsymbol{r},t)\,\phi_2(\boldsymbol{r},t)+S_2(\boldsymbol{r},t)\,,\end{aligned} \tag{3}$$

$$\frac{\partial}{\partial t}C(\boldsymbol{r},t) \;=\; \beta\nu\left(\Sigma_{\text{f},1}(\boldsymbol{r},t)\,\phi_1(\boldsymbol{r},t)+\Sigma_{\text{f},2}(\boldsymbol{r},t)\,\phi_2(\boldsymbol{r},t)\right)-\lambda C(\boldsymbol{r},t) \tag{4}$$

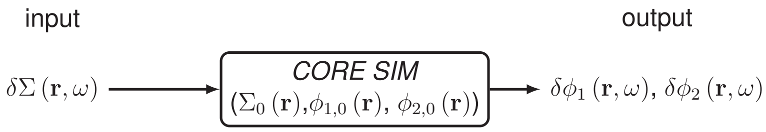


Fig. 2.
Illustration of *CORE SIM*, calculating the neutron flux fluctuations triggered by perturbations of the macroscopic cross-sections.

with all symbols carrying their usual meaning, in the frequency domain. For this purpose, all variables are expanded about their steady-state values, $X(r, t) = X_0(r) + \delta X(r, t)$. Products of the (time-dependent) deviations $\delta X(r, t)$ are neglected in order to linearize the equations. Fourier transformation of the deviations $\delta X(r, t) \to \delta X(r, \omega)$ finally leads to the frequency-domain equations. The employed numerical techniques to solve them are given in Ref. *[8]*. Practically, *CORE SIM* calculates the variations $\delta\phi_1(r, \omega)$ and $\delta\phi_2(r, \omega)$ of the neutron flux (output) based on a given distribution $\delta\Sigma(r, \omega)$ of perturbations (input) of the macroscopic cross-sections. The procedure is illustrated in **Figure 2**. The calculation is based on externally provided distributions of the cross-sections $\Sigma_0(r)$ and on the steady-state distribution ($\phi_{1,0}(r)$, $\phi_{2,0}(r)$) of the neutron flux. The latter is calculated by *CORE SIM* in a steady-state calculation prior to the calculation of the fluctuations $\delta\phi_1(r, \omega)$ and $\delta\phi_2(r, \omega)$. *CORE SIM* sets criticality by renormalizing the fission cross-sections with the multiplication factor k_{eff}.

2.1.3 Preparation of the *CORE SIM* simulation

Both the cross-sections $\Sigma_0(r)$ and their perturbations $\delta\Sigma(r, \omega)$ are provided via a *DYN3D* calculation that precedes the *CORE SIM* run. Using this strategy, the complex configuration of the reactor's material data is covered in the simulation. Furthermore, the specific impact of the fuel-assembly gap variations on the cross-sections, which depends on various parameters (T_{fue}, T_{mod}, ρ_{mod}, c_{bor}, burnup, fuel-assembly type), gets incorporated.

Figure 3 illustrates the procedure. Based on a model of a PWR (with straight fuel assemblies), *DYN3D* performs a steady-state calculation, yielding the steady-state distribution of the cross-sections $\Sigma_{0,DYN3D}(r)$ with also the thermal-hydraulics variables converged. The distribution of effective fuel-assembly pitches $\{p_n(z_m), n = 1, \ldots, 193, m = 2, \ldots, 35\}$ (cf. Eq. (1)), representing the homogeneous fuel-assembly gap elongation and the sinusoidal axial shape, is denoted as Π. A modified version of *DYN3D* with a cross-section library covering variations of the effective fuel-assembly pitch $p_n(z_m)$ (cf. *[7]*) interpolates the set of cross-sections $\Sigma_{\Pi,DYN3D}(r)$ that corresponds to the distribution of fuel-assembly pitches Π on the one hand and to the complex distribution of the parameters listed above on the other hand. The actual perturbation $\delta\Sigma$ of the cross-sections Σ is their deviation against the steady-state Σ_0.[1] The cross-section perturbations that can be applied in *CORE SIM* are calculated as follows:

$$\delta\Sigma_{\text{a},1}(n_{\text{Ch}}, n_z, \omega) = (\Sigma_{\text{a},1,\Pi,DYN3D}(n_{\text{Ch}}, n_z) - \Sigma_{\text{a},1,0,DYN3D}(n_{\text{Ch}}, n_z)) \cdot \delta(\omega - \omega_0), \tag{5a}$$

$$\delta\Sigma_{\text{a},2}(n_{\text{Ch}}, n_z, \omega) = (\Sigma_{\text{a},2,\Pi,DYN3D}(n_{\text{Ch}}, n_z) - \Sigma_{\text{a},2,0,DYN3D}(n_{\text{Ch}}, n_z)) \cdot \delta(\omega - \omega_0), \tag{5b}$$

$$\delta\Sigma_{\text{r}}(n_{\text{Ch}}, n_z, \omega) = (\Sigma_{\text{r},\Pi,DYN3D}(n_{\text{Ch}}, n_z) - \Sigma_{\text{r},DYN3D}(n_{\text{Ch}}, n_z)) \cdot \delta(\omega - \omega_0), \tag{5c}$$

$$\delta\Sigma_{\text{f},1}(n_{\text{Ch}}, n_z, \omega) = (\Sigma_{\text{f},1,\Pi,DYN3D}(n_{\text{Ch}}, n_z) - \Sigma_{\text{f},1,0,DYN3D}(n_{\text{Ch}}, n_z)) \cdot \delta(\omega - \omega_0), \tag{5d}$$

$$\delta\Sigma_{\text{f},2}(n_{\text{Ch}}, n_z, \omega) = (\Sigma_{\text{f},2,\Pi,DYN3D}(n_{\text{Ch}}, n_z) - \Sigma_{\text{f},2,0,DYN3D}(n_{\text{Ch}}, n_z)) \cdot \delta(\omega - \omega_0), \tag{5e}$$

with the discrete spatial setup (n_{Ch}, n_z) according to **Figures 1a** and **1b**. Note that the *DYN3D* levels $m = 4$ and $m = 5$ are homogenized, making *CORE SIM* level $n_{\text{Ch}} = 4$. Similarly, $m = 31$ and $m = 32$ make $n_{\text{Ch}} = 30$.

1) Note that coefficients translating the elongations to cross-section deviations, as used in the simulations shown in Ref. *[11]*, are obsolete for the current approach.

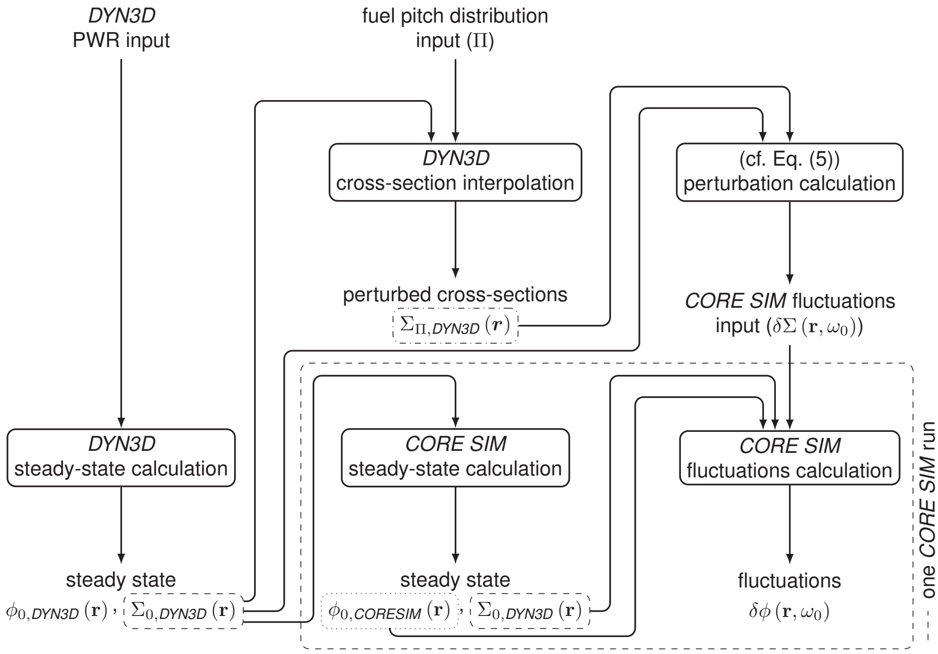


Fig. 3.
Procedure of coupled calculations performed in order to simulate the homogeneous fuel-assembly gap variation with *CORE SIM*.

The symbol $\delta(\omega - \omega_0)$ indicates that the cross-section perturbation acts at the frequency $\omega = \omega_0$. Finally, with the steady- state distribution $\Sigma_{0,DYN3D}$ and the perturbations $\delta\Sigma$ at hand, *CORE SIM* calculates the neutron flux fluctuations as described in Sec. 2.1.2.

2.2 Results

For the simulation, the chosen gap-fluctuation amplitude is 1.6 mm, which is the nominal gap width *[1]*. The chosen oscillation frequency is $\omega_0 = 2\pi \cdot 1.0$ Hz. **Figure 4** presents the simulated neutron flux fluctuations for the thermal group. The maximum magnitude is approx. 4.5 %. It is located in the outer regions in x-direction **(Figure 4a)** at mid axial level **(Figure 4b)**. The lowest magnitude is found in the central region in x-direction and at the bottom and the top in axial direction. The axial shape of the magnitudes is C-like. **Figure 4c** shows that the fluctuations are out-of-phase for comparing the left and the right core half. Along the axial direction **(Figure 4d)**, the fluctuations are in-phase. Comparing different channels with one another, either in-phase or out-of-phase behavior is found. The behavior corresponds to the phase relations seen in the horizontal view **(Figure 4a)**.

2.3 Measured values

For convenience, **Figure 5** briefly presents measured data of a 4-loop Vor-Konvoi reactor at nominal power at end of cycle (details about the data can be found in Ref. *[4]*). The standard deviation takes values in the range of percents. Along the central lines (G, J), the magnitude is lower than in the outer lines (≥N, ≤C). In the axial view, the magnitude has a bulgy shape. The phase (determined by the cross-spectral densities of the considered signals with the signal of

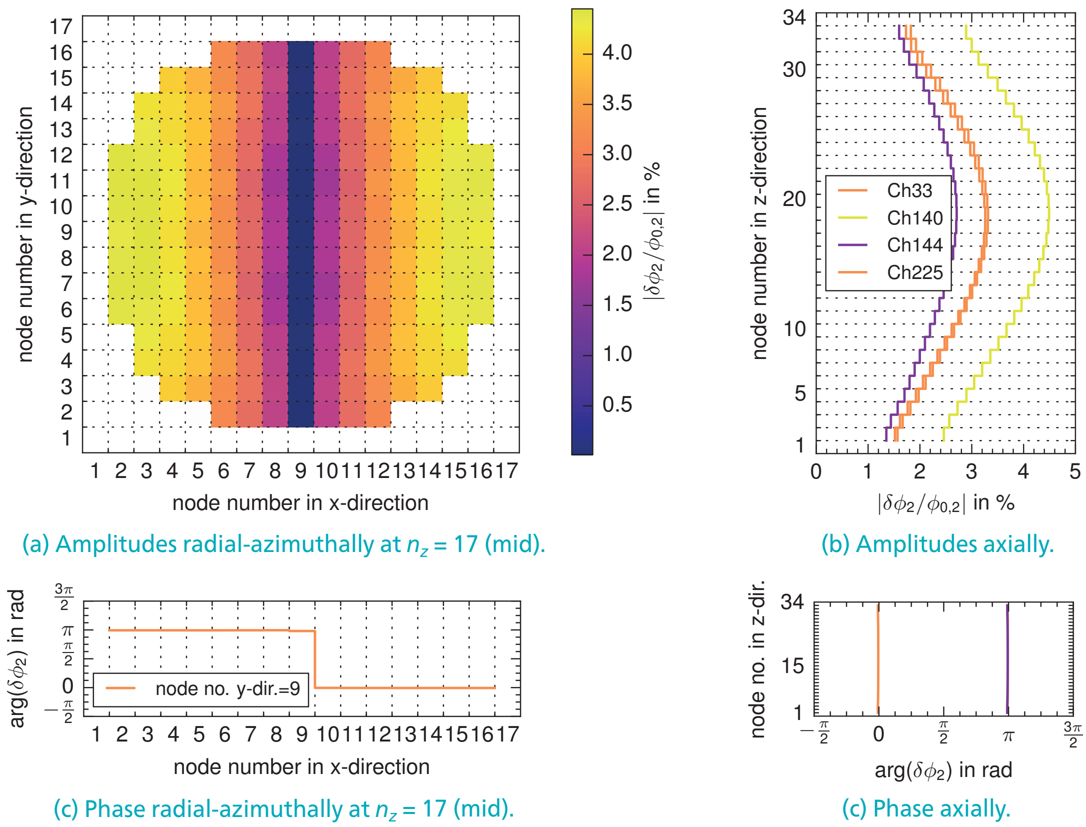
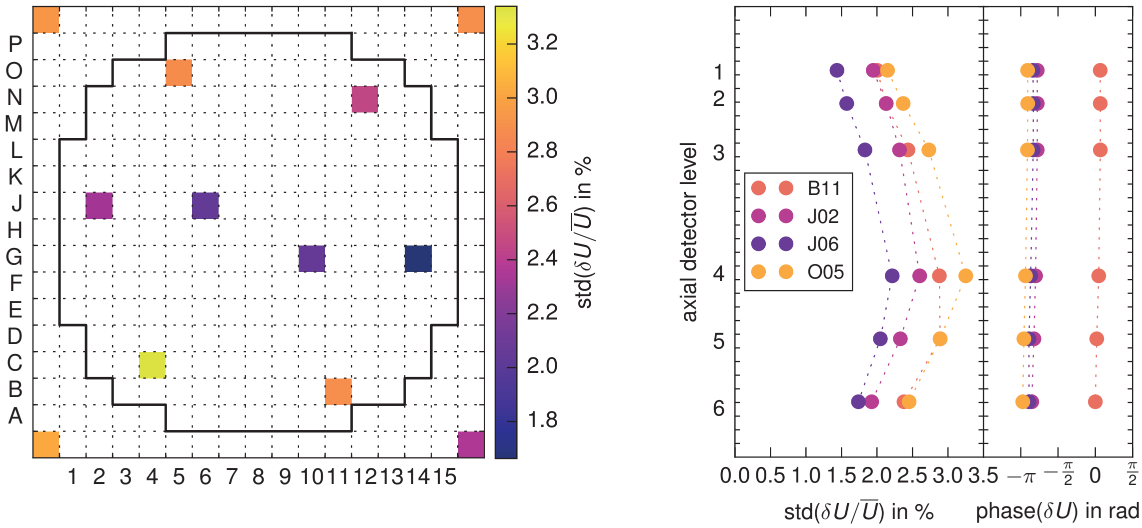


Fig. 4.
Spatial distribution of the induced neutron flux fluctuations $\delta\phi_2$ for the thermal energy group calculated with *CORE SIM* for a homogeneous fluctuation of all fuel-assembly gaps in x-direction at $\omega_0 = 2\pi \cdot 1.0$ Hz with a sinusoidal axial shape. The upper panel shows the relative amplitudes $|\delta\phi_2/\phi_{0,2}|$ of the fluctuations and the lower panel shows the phase $\arg(\delta\phi_2)$ of the fluctuations. The phase has the input perturbation, for which $\arg(\delta\Sigma) = 0$, as its reference. (In **Figure 4d**, the curve of Ch144 overlaps with those of Ch140 and Ch225.)



(a) Radial view.

(b) Axial view (phase ref.: B11-6).

Fig. 5.
Measured data of neutron flux fluctuations. Standard deviation std() of detector signals normalized w. r. t. their mean values and phase of the fluctuations w. r. t. those at detector B11-6.

location B11-6 as the reference) demonstrates the axial in-phase and radial out-of-phase behavior known from this type of reactor (cf. *[4]*).

2.4 Discussion

The presented simulation overcomes the defect of the small fluctuation magnitudes that resulted for the simulation of the "reflector effect" (cf. *[5,11]*) while preserving the characteristic phase relations of the fluctuations (see **Figures 4c**, **4d**, and **5b**). The distributions of magnitudes in the axial and in the radial direction are similar to the measured ones (see **Figures 4a, 4b, 5**).[2] The axial shape corresponds to the assumed axial bow shape[3] of the fluctuation magnitudes.

It has to be emphasized that the scenario considered in this article is marked by vast simplifications. Nevertheless, it reproduces relevant main features of the measured neutron flux fluctuations. Therefore, the assumed homogeneous gap fluctuation is among those scenarios potentially taking place in the actual reactor. On the other hand, a proper mechanism that drives such behavior has not been found, yet.

Research of the near future needs to focus on finding plausible mechanisms that are responsible for the fuel assembly vibration as a consequence of coolant. Furthermore, the trend of the magnitudes in the horizontal view should be further investigated. As seen in **Figure 4a**, the trend seems to be only little dependent on the kind of fuel assemblies; the trend seems to be a geometrical effect. With regard to the simplicity of the simulation shown, the use of the effective fuel-assembly pitch variation has not been validated, yet. This fact may be tackled in near future as well.

3 Conclusion

Neutron flux fluctuations of KWU PWRs show dominant patterns. Based on the as- sumption that the gaps of all fuel assemblies fluctuate in a synchronous manner, the corresponding neutron flux fluctuations are simulated with *CORE SIM* in the frequency domain. The obtained fluctuation patterns are similar to the measured patterns and the obtained fluctuation magnitudes are in the range of percents as in the measurements. Therefore, the assumed scenario is a potential candidate for being the main perturbation source triggering the observed neutron flux fluctuation patterns. Future research needs to address the lack of a mechanism that explains the excitation of fuel-assembly vibrations by coolant-flow fluctuations.

Acknowledgement

This work was supported by the German Federal Ministry for Economic Affairs and Energy (project NEUS, grant number 1501587). The responsibility for the content of this publication lies with the authors. The authors thank Marcus Seidl for discussion.

References

[1] (German) Reactor Safety Commission (RSK), "PWR neutron flux oscillations," RSK Statement (457th meeting on 11.04.2013), 2013. http://www.rskonline.de/en/meeting457

[2] M. Seidl, K. Kosowski, U. Schüler, and L. Belblidia, "Review of the historic neutron noise behavior in german KWU built PWRs," Progress in Nuclear Energy, vol. 85, pp. 668 – 675, 2015. http://www. sciencedirect.com/science/article/pii/S0149197015300652

[3] J. Runkel, "Rauschanalyse in Druckwasserreaktoren," Ph.D. dissertation, Universität Hannover, 1987.

[4] M. Viebach, N. Bernt, C. Lange, D. Hennig, and A. Hurtado, "On the influence of dynamical fuel assembly deflections on the neutron noise level," Progress in Nuclear Energy, vol. 104, pp. 32 – 46, 2018. http://www.sciencedirect.com/science/article/pii/S0149197017302147

[5] M. Viebach, C. Lange, N. Bernt, M. Seidl, D. Hennig, and A. Hurtado, "Simulation of low-frequency pwr neutron flux fluctuations," Progress in Nuclear Energy, vol. 117, p. 103039, 2019. http://www. sciencedirect.com/science/article/pii/S0149197019301349

[6] L. Torres, D. Chionis, C. Montalvo, A. Dokhane, and A. García-Berrocal, "Neutron noise analysis of simulated mechanical and thermal-hydraulic perturbations in a pwr core," Annals of Nuclear Energy, vol. 126, pp. 242 – 252, 2019. http://www.sciencedirect.com/science/article/pii/S0306454918306303

[7] M. Viebach, C. Lange, M. Seidl, Y. Bilodid, and A. Hurtado, "Neutron noise patterns from coupled fuel-assembly vibrations," in PHYSOR 2020: Transition to a Scalable Nuclear Future, Cambridge, United Kingdom, March 29 -April 2, 2020, 2020.

[8] C. Demazière, "CORE SIM: A multi-purpose neutronic tool for research and education," Annals of Nuclear Energy, vol. 38, no. 12, pp. 2698 – 2718, 2011. http://www.sciencedirect.com/science/article/ pii/S0306454911002210

[9] U. Rohde, M. Seidl, S. Kliem, and Y. Bilodid, "Neutron noise observations in German KWU built PWRs and analyses with the reactor dynamics code DYN3D," Annals of Nuclear Energy, vol. 112, pp. 715 – 734, 2018. http://www.sciencedirect.com/science/article/pii/S0306454917303687

[10] U. Rohde, S. Kliem, U. Grundmann, S. Baier, Y. Bilodid, S. Duerigen, E. Fridman, A. Gommlich, A. Grahn, L. Holt, Y. Kozmenkov, and S. Mittag, "The reactor dynamics code DYN3D – models, validation and applications," Progress in Nuclear Energy, vol. 89, pp. 170 – 190, 2016. http://www.sciencedirect.com/science/article/pii/S014919701630035X

[11] M. Viebach, N. Bernt, C. Lange, D. Hennig, and A. Hurtado, "Frequency-Domain Investigation on the Neutron Noise in KWU PWRs," in 49th Annual Meeting on Nuclear Technology, Berlin, Germany, May 14-65, 2018, 2018.

Authors

Marco Viebach
marco.viebach@tu-dresden.de
Dr.-Ing. Carsten Lange
Prof. Dr.-Ing. Antonio Hurtado

Chair of Hydrogen and Nuclear Energy
Technische Universität Dresden
George-Bähr-Str. 3b,
01069 Dresden, Germany

2) The radial-azimuthal pictures are rotated by 90°, which would not be the case for considering the fuel-assembly bow exclusively in y- rather than in x-direction. Note that the x- and y-direction are equivalent in the underlying model. In the real reactor, exclusive consideration of only one direction is impossible. Therefore, the lack of the 90°-rotational symmetry in the measured data indicates an inherent asymmetry.

3) See Ref. *[11]* for a comparison of the results for various bow shapes.

nucmag.com

atw

International Journal
for Nuclear Power

Subscription

I would like to subscribe from now on to the atw – International Journal for Nuclear Power.

☐ Mr ☐ Ms

Surname, First Name

Organization

Sector of your organisation

☐ Industry ☐ Utilities ☐ Research/Education
☐ Consulting/Services ☐ Expert organization ☐ Administration
☐ Association ☐ Other:

Order No.

Street

Postal Code City Country

Telephone, E-mail

VAT No. (EU countries except Germany)

Billing address (if different from subscription address):

☐ Mr ☐ Ms

Surname, First Name

Organization

Street

Postal Code City Country

Telephone, E-mail

You will receive the atw for a price of:

- **Annual subscription – 9 issues 183.50 €**
  (20.38 € per issue/copy instead of 23.55 € per single issue/copy)

Preferred payment method (please tick):

☐ By invoice

☐ By SEPA Direct Debit

Name of bank

IBAN

BIC

☐ **I agree to the terms and conditions below.**

Date Signature

Terms and conditions

Prices for annual subscription outside Germany and for single issues excluding postage.

Prices including 5 % VAT for Germany and all EU member states without VAT number. For EU member states with VAT number and all other countries the price for annual subscription will be reduced to 174.77 €.

The publisher must be notified of cancellation of the subscription no later than 4 weeks before the end of the subscription period. Unless terminated with a notice period of 4 weeks to the end of the subscription period, the subscription will be extended for a further year in each case under the subscription terms applicable at the time.

Right of cancellation: This order may be cancelled within 14 days of the order form being received at INFORUM Verlags- und Verwaltungs-gesellschaft mbH, Robert-Koch-Platz 4, 10115 Berlin, Germany.

Please send your order to:

INFORUM Verlags- und
Verwaltungsgesellschaft mbH
Petra Dinter-Tumtzak
Robert-Koch-Platz 4
10115 Berlin, Germany

Fax: +49 30 498555-18
or order online: www.nucmag.com/shop