SIMULATE-3K Analyses of Neutron Noise Response to Fuel Assembly Vibrations and Thermal-Hydraulics Parameters Fluctuations

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Abstract - *This paper presents a systematic analysis of reactor neutron noise behavior simulations when fuel assembly mechanical vibrations and core coolant inlet temperature fluctuations are introduced. To this aim, the advanced transient nodal code SIMULATE-3K (S3K) is used to investigate the response of the neutron detectors to introduced perturbations in a Swiss pressurized water reactor (PWR). In this context, the existing S3K core model of this PWR is enhanced by developing and assessing the incore and excore detector models. After that, a series of fuel assembly vibration patterns, e.g. variation of the number of vibrating assemblies and the magnitude of the vibration amplitude, along with coolant inlet temperature fluctuations have been introduced in order to assess the response of the neutron noise signal, both its amplitude and its spatial distribution (radial and axial). Results show that, the neutron noise response has almost a linear correlation to both the number of vibrating assemblies and the magnitude of the vibration amplitude. Finally, a preliminary assessment of the effect of bowing on the neutron noise level has been carried out and results show a clear impact on both noise level and its axial distribution. This systematic analysis illustrates clearly the capability of S3K to simulate such phenomena.*

Key words: *neutron noise, fuel assemblies vibration, fuel assemblies bowing, inlet temperature fluctuation.*

I. INTRODUCTION

Neutron noise is an inherent stochastic process of all nuclear reactors, characterized by fluctuations of both neutronic parameters (e.g. number of neutrons per fission, neutron flight path, etc.) and mechanical components vibration (e.g. core barrel oscillations, fuel assembly vibrations etc.). An increase of the neutron noise amplitude trend, measured by the monitoring systems of several SIEMENS pre-Konvoi type pressurized water reactors (PWR), has been observed during the last decade in several European countries. The neutron noise amplitude is found to increase both during the cycle and also from cycle to cycle. The within-cycle increase has been well described in the literature, and it corresponds to the decrease of boron concentration and the increase of magnitude of the negative moderator temperature coefficient (MTC) as the burnup increases [1]. However, the cycle-to-cycle increase of neutron noise is a phenomenon that has not been yet fully understood. Although this trend of neutron noise amplitude increase has not been yet found to be related to any safety issue [2], it gives rise occasionally to some operational problems forcing the reactor to be operated at reduced power levels. So far, only hypotheses, and no definitive explanations, have been given about this unexpected behavior of the cycle-to-cycle increase in the neutron noise level. One potential root cause, among others, could be the introduction of new fuel assembly types in the last decade in the above-mentioned reactor cores with the tendency for increased vibrational behavior. More specifically, the spacer springs of these fuel assemblies have lower stiffness mechanical properties and are therefore, less resistant to lateral movements induced by the coolant turbulent flows. In addition, high neutron levels were historically related to the presence of a feed-water preheater in the steam generator of most of the pre-Konvoi PWRs. The preheater could introduce strong temperature gradients on the coolant and eventually could influence the neutron noise levels [2], which demonstrate the complexity of the neutron noise topic and its dependency on the neutronic, thermal-hydraulic and material properties parameters.

The goal of this paper is twofold. First, the assessment of the capability of the S3K code to correctly simulate the propagation of different perturbations on the neutron flux population, i.e. neutron noise. Second, the performance of a systematic analysis of reactor neutron noise behavior when fuel assembly mechanical vibrations and/or core coolant inlet temperature fluctuations are introduced. Section II, describes the S3K model that was used and emphasizes the model enhancements that were introduced. The analysis

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results for all the examined scenarios are presented in Section III, followed by the conclusions and the planned future work.

II. MODEL DESCRIPTION

The Laboratory for Reactor Physics and System Behavior (LRS) of the Paul Scherrer Institute (PSI) has developed over the years validated CASMO/SIMULATE models for all the Swiss nuclear reactors in collaboration with the national regulator [3]. In the same framework, SIMULATE-3K (S3K) models for the Swiss boiling water reactors (BWRs) were comprehensively validated against stability tests and other transient scenarios [4]. For the purpose of this work, the validated CASMO/SIMULATE3 models along with an associated S3K model of a Swiss PWR were updated with incore and excore detector models in order to simulate the response of neutron noise signal to the possible perturbations in the core, such as inlet coolant temperature fluctuations and fuel assembly vibrations.

1. Incore and excore neutron detector models development

In order to allow comparison between the measured incore detectors plant data and the simulated results, an incore neutron detector model, for the S3K code, has been developed based on the plant instrumentation configuration. The incore detector model is composed of 36 detectors distributed at six different azimuthal locations and at six different axial levels. It should be noted that, the model development follows the code developer methodology and specifications [5, 6].

In addition, an excore neutron detector model was developed, in order to investigate the neutron noise response due to the fast spectrum. The model evaluates the excore detector response d_n of a detector that is located at node n as a weighted average of the nodal fission power:

$$d_n = \sum_k \sum_{ij} w_{n,ij,k} RPF_{ij,k} = \sum_k \alpha_{n,k} \sum_{ij} r_{n,ij} RPF_{ij,k} \quad (1)$$

where, $RPF_{ij,k}$ is the nodal fission power in the node ij,k. Moreover, the nodal weighting factor ($w_{n,ij,k}$) is separable in a radial ($r_{n,ij}$) and an axial component ($\alpha_{n,k}$) [7]. The S3K code has the capability to evaluate the radial weighting factors based on a single energy group neutron transport kernel. The relative influence of each assembly to every excore detector corresponds to the attenuation Φ of fast neutrons along a ray (r) which is drawn from every assembly to every sub-interval along the vessel wall [7]:

$$\Phi(r) \sim \frac{1}{r} e^{-\Sigma_r r} \quad (2)$$

The radial transport model assumes by default a constant macroscopic removal cross section $\Sigma_r=0.115cm^{-1}$ for the entire path regardless the medium that the neutrons are traversing (e.g. fuel, coolant, steel, etc.).

Preliminary calculations were performed and the radial weighting factors evaluated by the S3K code were compared against MCNP results, based on a verified methodology developed at the LRS-STARS program in a previous work [8].

The comparison showed that there is a significant difference between MCNP and S3K for the radial weighting factors of the fuel assemblies that are located close to the excore detector (i.e. first and second fuel assembly ring). This was improved by increasing the macroscopic removal cross section to a value of $\Sigma_r=0.201cm^{-1}$ (which corresponds to an MCNP-calculated value by taking into account the specific geometrical characteristics and material composition of the analyzed PWR).

Concerning the axial weighting factors, the S3K code does not offer an internal calculation as in the case of the radial factors. Therefore, the current work used the axial weighting factors which have been previously calculated by the abovementioned verified methodology based on MCNP calculations [8].

Dedicated analysis and further enhancements of the excore detector model is planned to be performed in the future.

2. Fuel assembly vibration model description

One of the latest versions of the S3K code (v2.06.00) offers the capability to simulate fuel assembly lateral movement in the *x*- or/and *y*-direction by automatically modifying randomly the sizes of the water gaps which surround the fuel assembly of interest [6]. This model is based on the delta gap model introduced in the CASMO and SIMULATE codes to model assembly bowing in PWRs [9]. The delta gap model allows a gap at any side of the fuel assembly to be modified by an incremental amount δ [9].

In the framework of this work, an external MATLAB script was developed for evaluating the delta gap sizes at any side of the fuel assemblies which have been selected to oscillate. This script ensures that the delta gap sizes are preserved in all four sides of the fuel assembly at every time step. In other words, when the delta gap on the left side of an assembly changes by $+\delta$ then the delta gap on its right side will be automatically modified by $-\delta$ in order to mimic an assembly movement to the right direction (as illustrated in Fig 1).

Fig 1. Preservation of delta gap sizes on both sides of a vibrating fuel assembly *i*.

In addition, further enhancements of the delta gap model have been introduced to allow the user to explicitly define time dependent delta gap 2D maps. Therefore, the user can control the vibrational characteristics (i.e. displacement amplitude, nominal frequency of vibration, etc.) of any oscillating fuel assembly.

During this work, the model capabilities have been assessed and a series of calculations have been performed in order to investigate the dependence of neutron noise amplitude on different fuel assembly displacement patterns. Preliminary results of this systematic investigation are presented in section III.

III. RESULTS AND ANALYSIS

This section illustrates the impact of different perturbation scenarios on the neutron noise amplitude and behavior and its associated propagation in the core, both axially and radially. These scenarios comprise the oscillation of single or multiple fuel assemblies (cluster), the fluctuation of the coolant inlet temperature, and their combination. It is noted that all the transient calculations were performed using the S3K code for which the steady-state solution has been fully converged in order to eliminate potential numerical noise. Moreover, all the S3K calculations have duration of *35s* with a time step of *0.01*s to minimize the statistical error of the results in both time and the frequency domain.

1. Single fuel assembly oscillation and coolant inlet temperature fluctuation

This case examines how the different sources of stochastic perturbation are influencing the neutron noise amplitude and behavior over the core. In this context, three calculations are performed, i) the central fuel assembly of the core is randomly vibrating only in the *x* direction at the maximum possible displacement, ii) the core inlet temperature is randomly fluctuating with an amplitude of *1K*, and iii) combination of (i) and (ii).

Incore neutron detector instrumentation tubes were modelled at the center of all the fuel assemblies for all the calculations. Therefore, it is possible to evaluate the neutron noise propagation in both axial and radial directions. Moreover, the neutron noise is estimated in terms of the statistical quantity of coefficient of variation *CV*, which indicates the signals variation around the mean, defined as:

$$CV = 100\frac{\sigma}{\mu} \qquad (3)$$

where, μ and σ are the signals mean value and standard deviation, respectively.

Fig 2 shows the neutron noise levels at every radial incore location at the top-core axial level when the central fuel assembly $FA_{8,8}$ (location $i,j=8,8$) is randomly vibrating only in the *x* direction. As can be observed, the random vibration of $FA_{8,8}$ results in a symmetric spatial shape of neutron noise across the core, as expected. Both the neighboring assemblies in the same direction as the introduced vibration, i.e. $FA_{8,7}$ and $FA_{8,9}$, are strongly influenced by the lateral movement of the $FA_{8,8}$ and therefore, higher noise levels are present. Note that, the noise attenuates very fast as the distance from the vibrated assembly increases. These results illustrate the capability of the fuel vibration model of S3K to properly simulate the lateral dynamic movement of a single fuel assembly in one direction.

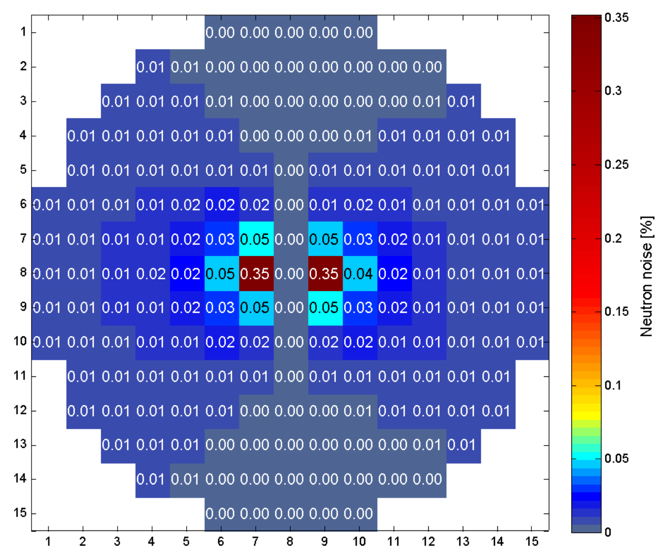

Fig 2: Neutron noise map at top-core axial level resulting from a random vibration of the central fuel assembly, only in the *x*-direction.

In neutron noise analysis, not only it is important to calculate the noise amplitude, but it is also very interesting to evaluate the noise behavior in the frequency domain. The in/ex-core detector spectrum (power spectral density) is a valuable quantity in noise analysis, as it includes important information of the noise characteristics, e.g. nominal frequency of vibration, etc. Fig. 3 represents the auto power spectral density (APSD) of neutron noise at the incore detector located right next to the vibrating assembly (and therefore, affected the most by the vibration) at the top-core axial level for the three calculations, i.e. i) random vibration of the central fuel assembly in the *x* direction with the maximum possible displacement, ii) random fluctuation of core inlet temperature with an amplitude of *1K*, and iii) combination of (i) and (ii).

As can be observed, the result of a randomly vibrating fuel assembly is a white noise in the neutron noise signals spectrum, as previously found [2]. In addition, it is interesting to observe the behavior of the random fluctuation of core coolant inlet temperature, where the introduction of white noise in the inlet temperature results in a non-white (colored) noise spectral shape of the neutron noise. More specifically, the spectrum is very strong in the low frequency range between *0* and *5Hz* while it is weaker and flat beyond *5Hz*. This behavior is due to the fact that the impact on reactivity is small when the inlet temperature changes rapidly (i.e. high frequencies) as the system does not manage to react on these fast inlet temperature fluctuations. However, at lower frequencies (i.e. when the inlet temperature changes smoother over time) the impact on reactivity will be stronger and therefore, the spectrum will have a $(v/\omega)^2$ shape [2]. Finally, the result of the combination of both fuel assembly vibration and coolant inlet temperature random fluctuations shows almost no changes in the APSD shape in the frequency range *0-5Hz*, however, then the spectrum starts to show higher values beyond *2Hz*. The resulting spectral shape of this case is qualitatively similar to the spectrum obtained from real plant data, which indicates that both fuel assembly oscillation and core coolant inlet temperature fluctuation could be the key sources of the neutron noise phenomenology.

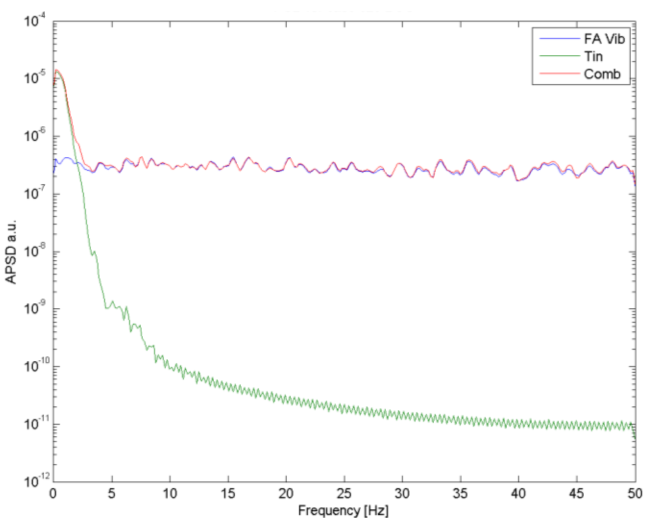

Fig. 3. Neutron noise auto power spectral density (APSD) due to single fuel assembly random oscillation (blue line), due to core inlet temperature fluctuation (green line), and due to combination of two effects (red line).

Table I shows the neutron noise level at an incore detector located right next to the vibrating assembly at the top-core axial level for the three scenarios. It is noted that, even a very small fluctuation of inlet temperature (e.g. deviation of ±*1K* from the average value) has a considerable impact on the neutron noise amplitude.

Table I. Neutron noise amplitude due to different perturbation scenarios

Scenario	Maximum neutron noise
Single FA oscillation only in *x* direction	*0.35%*
Inlet temperature fluctuation with *1K* amplitude	*0.34%*
Combination of two effects	*0.49%*

2. Neutron noise evolution within cycle and from cycle to cycle

In this section, the evolution of neutron noise amplitude during the cycle as well as during several operational cycles is presented. For that, real core loading patterns and core conditions (i.e. power level, core flow level, inlet core temperature, etc.) of six successive cycles have been used to simulate the impact of a randomly vibrating cluster of *3x3* fuel assemblies located at the central part of the core, on the noise level within each cycle and from cycle to cycle. All the assemblies within the cluster are vibrating in a synchronized way, i.e. the gap between assemblies belonging to the cluster remains constant. Calculations were performed at three burnup levels for every cycle; beginning of cycle (BOC), middle of cycle (MOC), and end of cycle (EOC). The results are summarized in Fig. 4, illustrating the normalized neutron noise amplitude evolution within cycle and over six cycles.

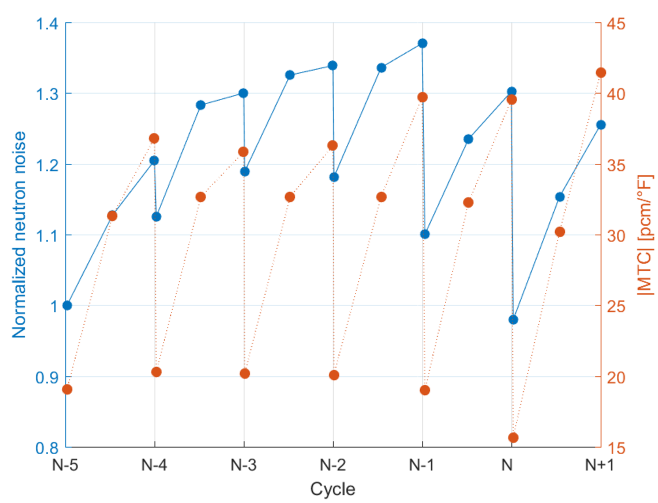

Fig. 4. Normalized neutron noise level (blue line) evolution of a vibrating fuel assembly cluster of size three, over six operational cycles and the respective absolute values of the absolute moderator temperature coefficient values (orange points).

As expected, S3K simulations properly predict an increase of the neutron noise level during the cycle, which is basically related to the increase of the magnitude of the negative moderation temperature coefficient due to the decrease of the boron concentration over the cycle.

Concerning the behavior of neutron noise from cycle to cycle, it is observed that, it is increasing in the first three cycles (*N-5*, *N-4*, and *N-3*), and then it decreases for the next cycles (*N*-2, N-*1*, and *N*). A close comparison shows that these differences in neutron noise behavior follow the evolution of the moderator temperature coefficient (orange points in Fig. 4) and therefore, the neutron noise evolution can be strongly depending on the different operating conditions (i.e. power level, core flow, core inlet temperature). Dedicated analysis on this topic is planned to be performed in the future. The impact of increasing the number of vibrating fuel assemblies on the neutron noise behavior is presented in the next paragraph.

3. Impact of the cluster size of vibrating fuel assemblies on neutron noise amplitude

The previous calculations focused on the impact of fuel assembly random vibration only in the *x* direction. This section examines, on the one hand, how the neutron noise level evolves as the cluster size of vibrating fuel assemblies located at the center of the core increases (i.e. *1x1*, *3x3*, *5x5*, *7x7*, *9x9*, and *11x11*), and on the other hand, how the neutron noise characteristics differ as the random vibration takes place only in the *x* direction or in both *x* and *y* directions.

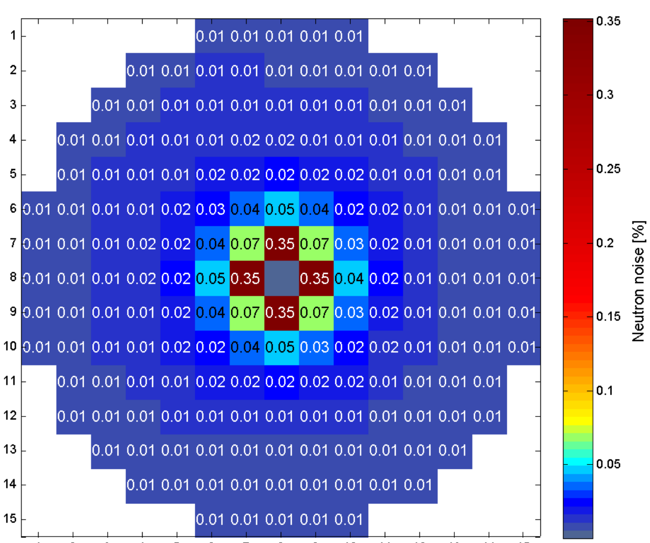

Fig 5: Neutron noise map at top-core axial level resulting from a random vibration of the central fuel assembly in both the *x* and *y* directions.

Fig 5 presents how the neutron noise amplitude is distributed radially at top-core axial level, as the central fuel assembly $FA_{8,8}$ is randomly vibrating in both *x* and *y* directions. It can be clearly seen that the noise spatial shape is fully symmetric in both directions. All four neighboring assemblies (i.e. $FA_{7,8}$, $FA_{9,8}$, $FA_{8,7}$, and $FA_{9,7}$) are affected the most. As the distance from the core center increases the neutron noise attenuates rapidly. It is interesting to mention that the noise level of the central fuel assembly is affected the least. This can be explained by the fact that the incore detectors are modeled to be located at the center of the fuel assembly. Therefore, the incore detector located in the center of $FA_{8,8}$ does not feel any difference as the assembly is randomly vibrating around its equilibrium position.

Moreover, Fig. 6 presents the importance of the number of fuel assemblies that are randomly vibrating as a cluster on neutron noise. The blue and red lines in Fig 6 show the neutron noise results when different cluster sizes are vibrating only in the *x* direction or in both *x* and *y* directions, respectively. The neutron noise level reaches its largest value when a cluster of eleven central fuel assemblies is randomly vibrating. For that configuration the noise level increases almost linearly up to *4.5* times, compared to the single fuel assembly vibration case, indicating that the number of randomly vibrating fuel assemblies strongly influence the neutron noise amplitude. Additionally, it is observed that the direction of the random oscillation does not affect so much the neutron noise level; randomly vibrating fuel assemblies only in *x* direction result in similar neutron noise levels if they oscillate in both directions.

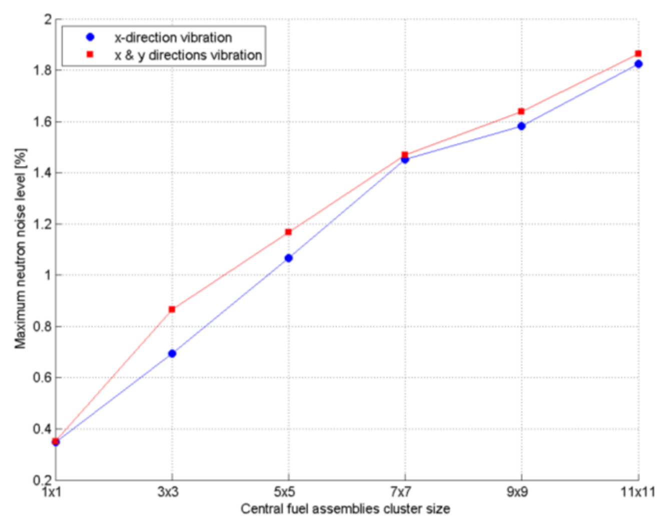

Fig. 6: Maximum neutron noise level for different fuel assembly cluster sizes which are randomly vibrating only in the *x* direction (blue circles) or in both *x* and *y* directions (red squares).

The neutron noise spatial shape resulting from a random vibration of a central cluster of *7x7* fuel assemblies only in *x* direction and both in *x* and *y* directions are presented in Fig. 7 and Fig. 8, respectively. These figures can be compared against Fig. 2 and Fig 5, which show the neutron noise spatial behavior due to single fuel assembly random vibration. It is observed that the neutron noise still has a symmetric shape depending on the direction of the fuel assembly vibrations. Clearly, the entire core is strongly influenced when a group of fuel assemblies (cluster) is vibrating in a synchronized way. That indicates that the fuel assembly vibration can affect the neutron noise not only locally (due to single assembly vibration) but also globally (due to vibration of a large cluster of assemblies).

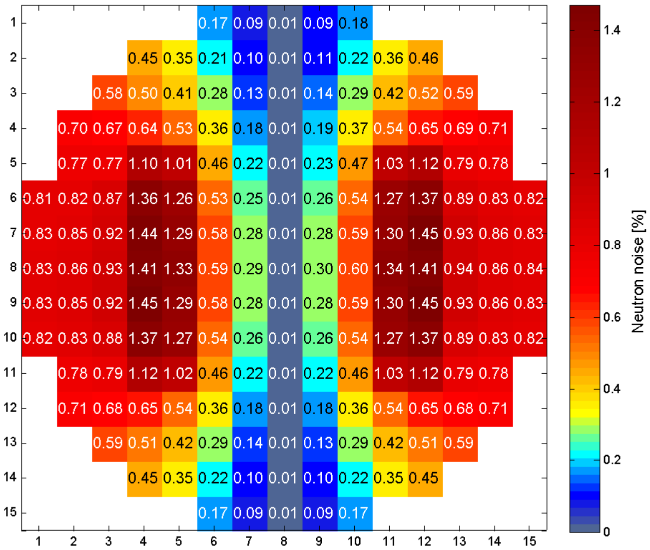

Fig. 7. Neutron noise map at top-core axial level resulting from a random vibration of a central fuel assemblies cluster of size 7, only in the *x* direction.

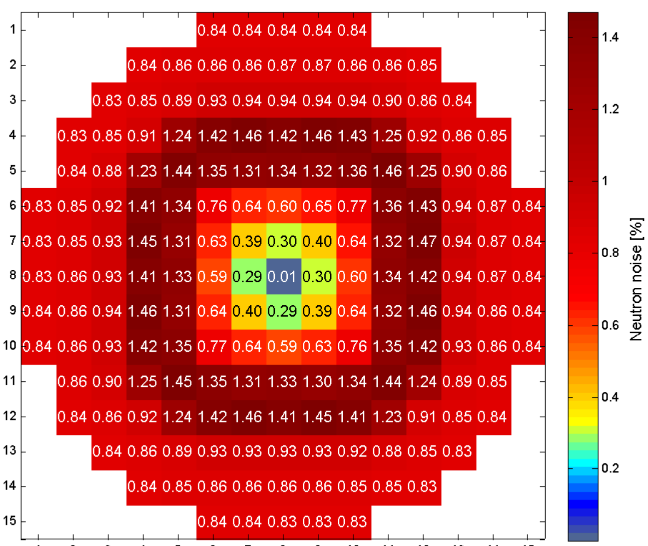

Fig. 8. Neutron noise map at top-core axial level resulting from a random vibration of a central fuel assemblies cluster of size 7, both in *x* and *y* directions.

Moreover, it can be seen that a random oscillation of a cluster results in higher neutron noise levels mainly in its neighborhood. Within the cluster the noise level is negligible in the central part (similar to single assembly vibration). This is due to the fact that the delta gap sizes of the central fuel assemblies are not influenced when the cluster they belong to is oscillating; in other words, the central fuel assemblies are not vibrating relative to the entire cluster. However, the noise levels become larger close to the periphery of the cluster.

4. Impact of maximum displacement of fuel assembly vibration on neutron noise amplitude

Previous studies have shown that the fuel assembly zircaloy spacer springs are completely relaxed after approximately one operating cycle [10]. Therefore, it is important to investigate the evolution of neutron noise amplitude when the amplitude of the fuel assembly oscillations is increasing. For this purpose, a series of calculations was performed with the central fuel assembly being randomly oscillating only in the *x* direction with three different ranges of maximum displacement, i.e. ¼, ½, and full maximum displacement. The results are presented in Table II, and they show that the neutron noise level increases almost linearly with the vibration maximum amplitude. This clearly indicates that possible increase of the fuel assembly maximum displacement over the cycles (due to decrease of the stiffness of the spacer springs), and even within the cycle, could possible result in larger neutron noise amplitudes, as observed from the real plant data.

Table II. Dependency of neutron noise on fuel assembly displacement amplitude

d_{max} [normalized values]	Maximum neutron noise
0.25	*0.09%*
0.50	*0.18%*
1.00	*0.35%*

5. Effect of bowed fuel assembly vibration on neutron noise amplitude

Lateral deformations of fuel rods and fuel assemblies occur often in light water reactors (LWRs) due to the strong hydraulic forces that act on the fuel assembly structures. These deformations are unwanted as they influence not only the refueling management but also the critical heat flux and eventually can affect the safety margins of the reactor.

From the neutron noise perspective, it is interesting to investigate what is the effect (if any) of bowed fuel assembly vibrations on the neutron noise behavior. Preliminary calculations were performed for two different axial bowed shapes, a *C* shape and an *S* shape, as presented in Fig 9.

The axial evolution of neutron noise for an unbowed fuel assembly which is randomly vibrating only in the *x* direction has been used as a reference case. The neutron noise amplitudes at different axial levels for the unbowed case are illustrated by the blue bars in Fig. 10 (from bottom to top-core). The noise levels are higher at the top compared to the bottom of the fuel assembly (linear dependency). This axially increasing profile of neutron noise can be related to the turbulent behavior of the coolant which becomes less dense as it flows axially to the top-core. Lower coolant density eventually results to higher neutron noise amplitude at the top-core axial level.

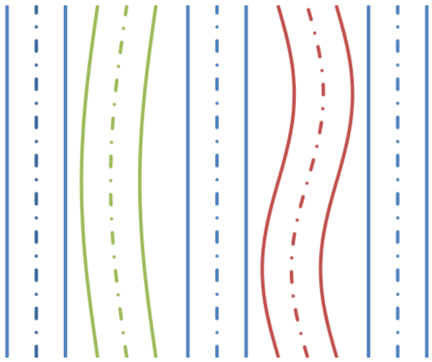

Fig 9. Axial delta gap *C* shape (green), and *S* shape (red) profiles are superimposed on the 2D radial delta gaps for simulating bowed fuel assembly vibrations.

The green and red bars in Fig 10 show the neutron noise levels at different axial levels when *C* or *S* axial shape profiles are superimposed on vibrating fuel assemblies, respectively. It is observed that the axial bowed shape of the vibrating assembly results to a similar axial profile of the neutron noise. For both the *C* and *S* shape cases (green and red bars, respectively) the highest noise level appear at the mid to top-core axial level (Level 4 and Level 5, respectively), corresponding to the combined effect of the maximum lateral deformation of the fuel assembly and the fact that top-core present higher noise levels compared to bottom-core, as it was explained for the unbowed case (blue bars)

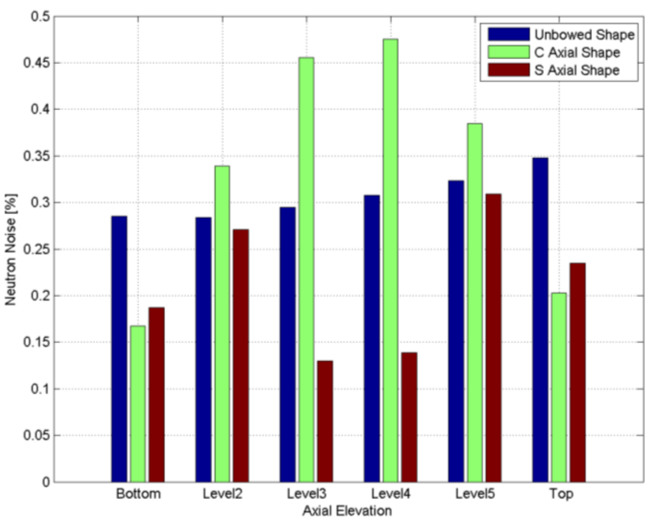

Fig 10. Neutron noise levels at different axial levels (bottom to top-core) when different axial profiles are imposed on vibrating fuel assemblies.

These calculations illustrate that the bow mechanism has a considerable impact on the neutron noise level as it can affect both the maximum neutron noise level and the neutron noise axial profile.

IV. CONCLUSIONS

During the last decade an increasing trend of the neutron noise levels for some specific type of PWRs in Germany, Switzerland and Spain has been observed. The cause of such noise level increase is still not fully understood.

The current research is an attempt to understand in more details the physical mechanism behind such phenomenon by carrying out a systematic study of the impact of fuel assembly vibration or/and core coolant inlet temperature fluctuations on the core neutron noise detector signals. For this purpose, the newly developed module in the transient nodal code S3K, with the possibility to simulate fuel assembly vibration by randomly changing the inter-assembly gap size has been assessed.

This paper demonstrates the model developments that have been introduced in order to establish a fuel assembly vibration methodology within the LRS-STARS program. The first results of this systematic analysis of the complex phenomenology of neutron noise show that the S3K code has the capability to qualitatively simulate both fuel assembly vibrations, and thermal-hydraulic parameters fluctuations, such as coolant temperature fluctuations. Several simulations were performed in order to investigate the impact of the number of vibrating assemblies and the size of the vibration amplitude on the level of the neutron noise. Both the neutron noise amplitude and its spatial (axial and radial) distribution were investigated revealing a linear response of the neutron noise on both the number of vibrating assemblies and the magnitude of vibration amplitude. Finally, a preliminary investigation of the effect of different bowed shapes of the vibrating fuel assemblies on the neutron noise response has been performed and results showed a clear impact on both noise level and its axial distribution. These results reveal the importance of further investigations on vibrating bowing assemblies using different patterns, which is the goal for further research.

Moreover, the impact of increasing the number of vibrating fuel assemblies from cycle to cycle will be systematically studied in the future. Also, the impact of vibrating fuel assemblies with specific nominal frequencies (not random vibration) will be studied in next work. Finally, further work is planned systematically comparing real plant data against simulation results in order to assess the S3K code capabilities in predicting incore and excore responses.

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REFERENCES

1. J.A. THIE, "Neutron noise sources in PWR's", *Progress in Nuclear Energy*, vol. 1, pp. 283-292 (1977).
2. M. SEIDL et al., "Review and historic neutron noise behavior in German KWU built PWRs", *Progress in Nuclear Energy*, vol. 85, pp. 668-675 (2015).
3. H, FERROUKHI et al., "Core modelling and analysis of the Swiss nuclear power plants for qualified R&D applications", *International Conference on the Reactor Physics, PHYSOR '08*, Interlaken-Switzerland (2008).
4. A. DOKHANE et al., "Transition to CASMO-5M and SIMUATE-3K for stability analyses of the Swiss BWRs", *Nuclear Technology*, vol. 183, pp. 341-352 (2013).
5. J.D. RHODES, "CASMO5 - A fuel assembly burnup program - User's manual, SSP-07/431 Rev 9", *Studsvik* (2015).
6. G.M. GRANDI, "SIMULATE-3K - Input specification, SSP-98/12 Rev. 18", *Studsvik* (2015).
7. G.M. GRANDI, "PWR Ex-core detector model in Studsvik CMS, SSP-05/425 Rev. 0", Studsvik (2005).
8. M. PECCHIA et al., "A methodology for evaluating weighting functions using MCNP and its application to PWR ex-core analyses", *submitted to Annals of Nuclear Energy* (2017)
9. T. BAHADIR, "CMS assembly bow model, SSP-97/34 Rev 1", *Studsvik* (2010)
10. A. BILLEREY, "Evolution of fuel rod support under irradiation - impact on the mechanical behavior of fuel assemblies", *IAEA-TECDOC 1454 Structural behaviour off fuel assemblies for water cooled reactors*, pp. 101-111 (2004)