DEVELOPMENT OF A METHOD FOR MEASURING THE MTC BY NOISE ANALYSIS AND ITS EXPERIMENTAL VERIFICATION IN RINGHALS-2

C. Demazière and I. Pázsit
Department of Reactor Physics
Chalmers University of Technology
SE - 412 96 Gothenburg, Sweden
demaz@nephy.chalmers.se; imre@nephy.chalmers.se

ABSTRACT

This paper deals with the estimation of the Moderator Temperature Coefficient of reactivity (MTC) by noise analysis. Previous experimental investigations showed that the MTC was systematically underestimated by a factor of two to five compared to its design-predicted value. In these measurements, the MTC was always determined by cross-correlating the neutron noise provided by a single in-core neutron detector with the local temperature noise given by a single core-exit thermocouple located at the top of the same fuel assembly, or of a neighbouring fuel assembly. It is shown in this paper via a noise measurement performed at the Swedish Ringhals-2 Pressurised Water Reactor (PWR) that the moderator temperature noise is radially strongly heterogeneous. Such a non-homogeneous temperature noise is proven theoretically to explain why the MTC was always underestimated in the previous experimental work when only the local temperature was used. A new MTC noise estimator, relying on the core-averaged moderator temperature noise, is thus proposed. This new estimator is demonstrated to provide an accurate MTC evaluation, as long as the radial structure of the moderator temperature noise can be measured. In the case of Ringhals-2, such in-core temperature measurements are carried out by Gamma-Thermometers (GTs), which in the frequency range of interest for the MTC investigation by noise analysis are working as ordinary thermocouples. This method, which is non-intrusive and free of calibration, can therefore be applied to monitor the MTC throughout the cycle.

1. INTRODUCTION

The Moderator Temperature Coefficient of reactivity (MTC) is an important safety parameter of Pressurised Water Reactors (PWRs). It plays a major role in the feedback mechanism and thus in the inherent stability of PWRs. In most countries like Sweden, the safety authorities require the MTC to be measured twice during each fuel cycle. The first measurement is performed at Hot Zero Power (HZP) and Beginning Of Cycle (BOC), in order to verify that the MTC is negative (preventing the consequences of a power increase). The second measurement is performed at Hot Full Power (HFP) and near the End Of Cycle (EOC), in order to check that the magnitude of the (negative) MTC is not larger than some prescribed limit (preventing the consequences of a large reactivity increase due to a cooldown event). Since the MTC magnitude is increasing with burnup (due to the decrease of the boron content), the second measurement is actually performed a few months before the EOC to determine if the reactor can be operated until its expected EOC.

The first measurement (reactor at HZP), which is based on a change of the core-inlet temperature of the core, is considered to be accurate and relatively easy to carry out since the reactivity change induced by the moderator temperature change is measured by a reactivity meter, and since the temperature is homogeneous throughout the core [1]. On the other hand, the second measurement was proven to be difficult to perform, and to be very inaccurate [2]. The at-power measurement techniques all rely on a pertubation of the inlet temperature of the core that the operator tries to compensate by other means (change of the boron concentration, or modification of the control rod insertion in most cases) in order to keep the reactor at full and steady power. The main reason for the inaccuracy is that these measurement techniques are time-consuming, and therefore many parameters, which cannot be measured but only estimated by core calculations, are also changing. The other main drawback of these techniques is that they disturb the plant operation, and induce a plant transient that the operator has to monitor for 12 to 24 h. Since core calculations are believed to estimate the MTC accurately, the trend nowadays for power utilities is to perform the BOC measurement, and then to rely completely on core calculations for the determination of the MTC variation through the fuel cycle.

Another measurement technique, relying on noise analysis and being therefore disturbance-free, was proposed a few years ago (see [3] for a complete list of references in this respect). In this technique, the neutron noise measured via an in-core Neutron Detector (ND) is cross-correlated to the moderator temperature noise measured by a core-exit Thermocouple (TC). This core-exit TC is usually located above the fuel assembly in which the ND is positioned, or above a neighbouring fuel assembly. In the frequency range of interest, it is assumed that the driving force for the flux fluctuations is the temperature noise, through the MTC. During such a measurement, the reactor is still at its steady state and full power. The cross-correlation of these two signals allows retaining only the MTC dynamics, from which the MTC coefficient can be directly estimated. However, many attempts to estimate the MTC by noise analysis showed that the MTC was systematically underestimated by a factor of two to five compared to its design-predicted value [3]. It was even noticed that this underestimation was constant during the fuel cycle and from cycle to cycle as long as the same pair of detectors is used for the MTC determination.

With the use of high-burnup fuel assemblies and MOX fuel assemblies in PWRs, monitoring the MTC might become crucial since these types of fuel assemblies have a positive contribution to the MTC. For the former, the reason lies with the high boron concentration required to compensate for the high reactivity of such fresh fuel assemblies at BOC. For the latter, the Pu-239 resonance is responsible for this positive effect on the MTC. Since at-power MTC core calculations were never benchmarked (and cannot be due to the inherent characteristics of the at-power measurements mentioned previously), relying on the BOC measurement and then on core calculations to estimate the at-power MTC is unacceptable. If the discrepancy in the MTC noise evaluation could be understood and a remedy found, the noise technique would become extremely interesting since the evaluation could be made through the entire fuel cycle.

Such a possibility arose recently since the present authors showed via a model that the main reason of the underestimation of the MTC by noise analysis could be that the temperature noise is radially heterogeneous in the core ([4] and [5]) and since at-power noise measurements in the Swedish Ringhals-2 PWR showed that the temperature noise was actually spatially non-homogeneous [6]. A new noise estimator that allows taking the spatial structure of the temperature noise into account was therefore proposed. In this paper, the results of an MTC noise measurement, performed in January 2002 in the Ringhals-2 PWR using this new noise estimator, are presented. First, the main results of the theoretical investigation carried out by the authors are recalled and the different MTC noise estimators described. Then the measurement set-up is presented in detail. Finally, the measurement is analysed and the MTC estimated. As will be seen in the following, the new MTC noise estimator provides a very good estimation of the actual MTC value.

2. DESCRIPTION OF THE MTC NOISE MEASUREMENT TECHNIQUE

2.1 TRADITIONAL MTC NOISE ESTIMATOR

In all the experimental work carried out so far, the MTC was estimated from the signals delivered by one in-core ND and a core-exit TC located at the top of the same fuel assembly or of a neighbouring fuel assembly. The so-called H_1^{biased} MTC noise estimator was always used for these estimations. This noise estimator can be defined in the frequency range 0.1 - 1.0 Hz as follows:

$$H_1^{biased}(\mathbf{r},\omega) = \frac{1}{G_0(\omega)} \frac{CPSD_{\delta\phi/\phi_0,\,\delta T_m}(\mathbf{r},\omega)}{APSD_{\delta T_m}(\mathbf{r},\omega)} \tag{1}$$

where the APSD and the CPSD stand for the Auto-Power Spectral Density and the Cross-Power Spectral Density respectively. The relative neutron noise $\delta\phi/\phi_0$ and the moderator temperature noise δT_m are both measured at the same radial position $\mathbf{r}$. $G_0(\omega)$ is the zero-power or open-loop reactor transfer function:

$$G_0(\omega) = \frac{1}{i\omega\left(\Lambda + \frac{\beta_{eff}}{i\omega + \lambda}\right)} \tag{2}$$

where β_{eff}, Λ, and λ are the effective fraction of delayed neutrons, the prompt neutron lifetime, and the one-group precusors decay constant respectively. As indicated on the l.h.s. of Eq. (1), this MTC noise estimator always gives a biased estimation of the MTC, i.e. the MTC was always observed to be underestimated by a factor of two to five.

2.2 NEW MTC NOISE ESTIMATOR

A recent theoretical investigation performed by the authors ([4] and [5]) showed that there are two main reasons that could explain why the MTC is underestimated. The first one lies with the fact that the temperature noise is measured in one point of the reactor (usually at the core-exit), whereas there is some experimental evidence that the temperature noise is strongly radially heterogeneous [6]. According to the MTC definition, the core-averaged temperature noise should be used while evaluating the MTC. The other reason for the MTC underestimation is that the reactor will not behave in a point-kinetic manner due to the spatial non-homogeneous structure of the temperature noise. The use of Eq. (1) implicitly assumes that point-kinetics is applicable. As a matter of fact, a correct, i.e. non-biased, MTC noise estimator was proposed by the authors in the frequency range 0.1 - 1.0 Hz:

$$H_1^{ideal}(\omega) = \frac{1}{G_0(\omega)} \frac{CPSD_{\delta\phi^{pk}/\phi_0,\,\delta T_m^{ave}}(\omega)}{APSD_{\delta T_m^{ave}}(\omega)} \tag{3}$$

In this ideal MTC noise estimator, the point-kinetic component $\delta\phi^{pk}$ of the neutron noise $\delta\phi$ and the core-averaged temperature noise δT_m^{ave} should be used. In the theoretical work mentioned previously, another new MTC noise estimator was also tested. This new $\tilde{H}_1^{biased}$ MTC noise estimator supposes that the core-averaged temperature noise could be measured, but still uses the total neutron noise $\delta\phi$ instead of its point-kinetic component $\delta\phi^{pk}$. Due to the latter, this noise estimator is also biased in the frequency band 0.1 - 1.0 Hz:

$$\tilde{H}_1^{biased}(\mathbf{r},\omega) = \frac{1}{G_0(\omega)} \frac{CPSD_{\delta\phi/\phi_0,\,\delta T_m^{ave}}(\mathbf{r},\omega)}{APSD_{\delta T_m^{ave}}(\omega)} \tag{4}$$

However, as was shown in the model calculations, the bias of this estimator is small (the deviation from point-kinetics is not significant).

2.3 COMPARISON BETWEEN THE TRADITIONAL AND THE NEW MTC NOISE ESTIMATORS VIA CORE MODELLING

The traditional MTC noise estimator given by Eq. (1) and the new MTC noise estimator given by Eq. (4) were both evaluated in a 2-D model representing a realistic PWR, i.e. a heterogeneous system [5]. The neutron noise was calculated by a so-called neutron noise simulator developed by the authors [7]. This simulator determines the spatially dependent neutron noise induced by any spatially dependent noise source, expressed in terms of fluctuations of the macroscopic cross-sections.

The moderator temperature fluctuations were thus assumed to be directly proportional to the macroscopic cross-section fluctuations via a space- and time-independent coefficient K as follows:

$$\delta T_m(\boldsymbol{r}, t) = K \times \delta\Sigma(\boldsymbol{r}, t) \tag{5}$$

Several noise source types were investigated, but in the following only the case of the removal macroscopic cross-section fluctuations will be presented. The noise source was then defined directly in the frequency domain through its spatial statistical properties, i.e. its CPSD as:

$$CPSD_{\delta\Sigma}(\boldsymbol{r}, \boldsymbol{r}', \omega) = \sigma^2(\hat{\boldsymbol{r}}) e^{-\frac{|\boldsymbol{r} - \boldsymbol{r}'|}{l}} \tag{6}$$

with

$$\sigma(\hat{\boldsymbol{r}}) = \frac{1}{1 - \left(\frac{\hat{\boldsymbol{r}}}{R + \delta R}\right)^2} \tag{7}$$

and

$$\hat{\boldsymbol{r}} = \frac{\boldsymbol{r} + \boldsymbol{r}'}{2}. \tag{8}$$

R is the core radius and $\delta R = R/5$. $\sigma^2(\hat{\boldsymbol{r}})$ is the shape function and represents the noise source strength, i.e. its APSD. The shape function given by Eq. (7) corresponds to some experimental evidence that the temperature noise was larger close to the core boundary than at the core centre [8]. In this model, l is called the correlation length of the temperature fluctuations and is supposed to be space independent. The correlation length indicates roughly the maximum distance between two points that can be considered as having a coherent behaviour. For greater distances, their behaviour can be assumed to be completely uncorrelated. Several correlation lengths were investigated, but only the results corresponding to l=150 cm will be presented in the following.

From this noise source, the neutron noise can be evaluated and the MTC noise estimators calculated accordingly. Such results are presented in the following Figs. 1 and 2 at a frequency of 1 Hz. The simulations show that the new MTC noise estimator gives a fairly good estimation of the MTC, for all possible locations of the neutron detectors. This suggests therefore that the deviation of the reactor response from point-kinetics does not play a significant role on the MTC estimation. The main reason of the MTC underestimation in all the experimental work carried out so far thus seems to be due to the radial non-homogeneous structure of the temperature noise throughout the core. Consequently, the MTC could be correctly estimated by noise analysis if the noise estimator given by Eq. (4) could be used, i.e. if the core-averaged temperature noise could be measured.

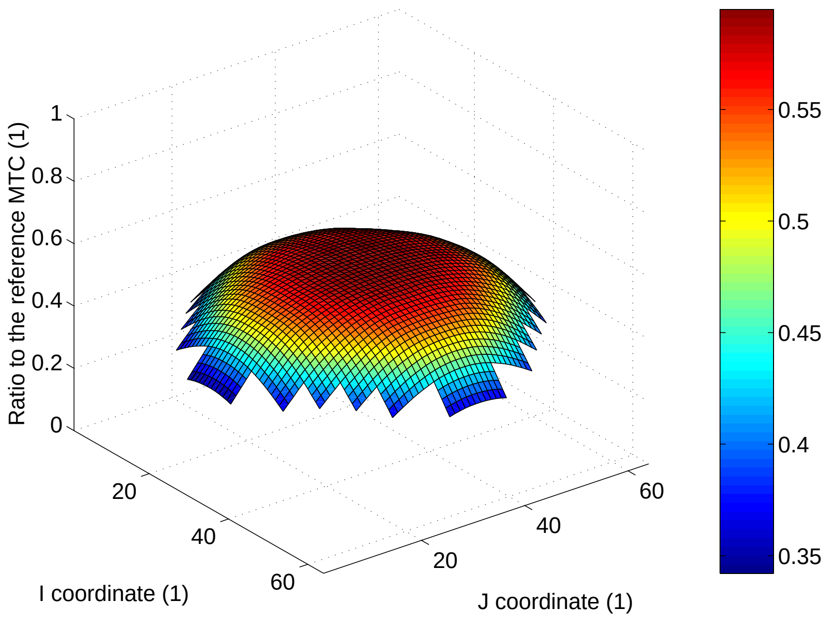

Figure 1. Ratio between the H_1^{biased} MTC noise estimator (i.e. the traditionally used one) and the actual value of the MTC

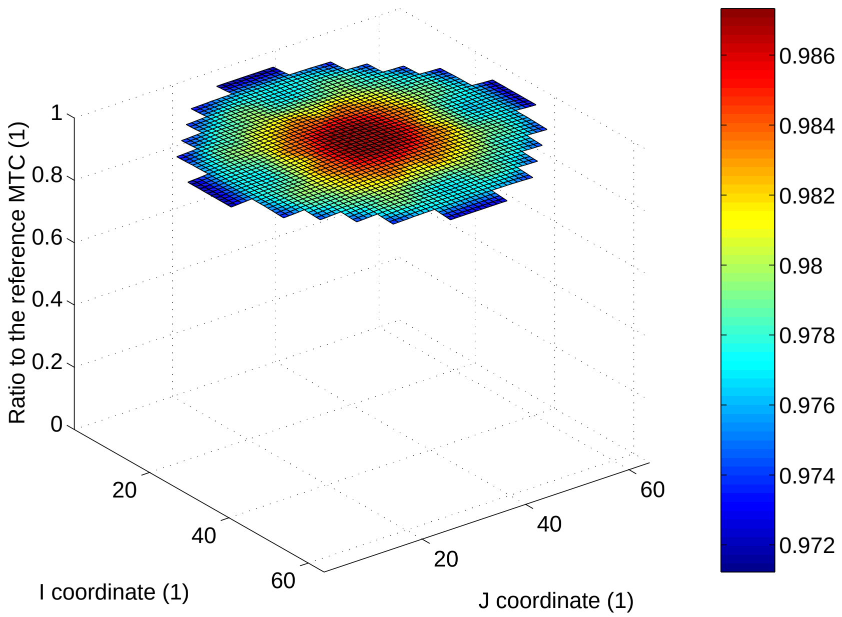

Figure 2. Ratio between the $\tilde{H}_1^{biased}$ MTC noise estimator (i.e. the recently suggested one) and the actual value of the MTC

2.4 USE OF THE NEW MTC NOISE ESTIMATOR IN RINGHALS-2

It is well known that Westinghouse type PWRs do not have any in-core temperature detectors, only a few core-exit TCs. At the Swedish Ringhals-2 PWR, 108 Gamma-Thermometers (GTs) are nevertheless installed permanently in the core. They are distributed in 12 detector strings, each of them containing 9 GTs located at different axial levels and covering the whole core active height. These GTs are of the RADCAL type [9]. In this design, an inner pin is heated by energy deposited mainly by gammas (elastic and inelastic collisions) and to a lesser extent by neutrons ((n, γ), (n, α), (n, p) reactions, elastic and inelastic collisions) [10]. One of the tips of the pin is insulated, so that the heating creates a temperature gradient along the pin. A differential thermocouple is used to measure the temperature drop along the pin, with the hot junction located at the insulated tip of the pin and the cold junction directly in contact with the coolant outside the GT housing. Since the cold and hot junctions have different thermal characteristics and due to their location measure different phenomena, the noise induced by both junctions have different properties and in particular response times [11].

The cold junction is located above the GT body and is direct contact with the coolant. Thus it responds very quickly to coolant temperature oscillations (with a thermal time constant typically around 0,1 s). This means that the cold junction acts as a low-pass filter of the coolant temperature noise with a cut-off frequency of a few hertz. The hot junction is thermally insulated within the inner body and has therefore a significantly more sluggish response (with a thermal time constant typically around 100 s). Consequently, the hot junction acts as a low-pass filter of the gamma/neutron flux with a cut-off frequency of a few hundredth of hertz.

In the frequency range of interest for the MTC investigation by noise analysis, i.e. 0.1 - 1.0 Hz, the GTs are therefore working as ordinary thermocouples [11], [12]. Therefore, the GTs installed at Ringhals-2 can be used to measure the core-averaged temperature noise. Together with an in-core ND, the new noise estimator given by Eq. (4) could be used to evaluate the MTC.

Such a noise measurement was recently performed at Ringhals-2 on January 16th, 2002. The purpose of this paper is to give an account of this measurement and the corresponding MTC noise estimations.

3. DESCRIPTION OF THE MTC NOISE MEASUREMENT PERFORMED IN RINGHALS-2

A noise measurement was carried out at the Swedish Ringhals-2 PWR during the fuel cycle 26, at a core-averaged burnup of 7.30 GWd/tHM (January 16th, 2002). This measurement was performed while the reactor was at steady state, and at full power. The measurement duration was about 25 minutes, and the sampling frequency was 8 Hz. In this noise measurement, all the available detectors (twelve GTs and two NDs) on one plane of the reactor, located at 30% of the core active height from its bottom (plane 7 in Fig. 3), were used by the data acquisition system. Likewise, a fuel assembly (assembly J10 in Fig. 3) was axially fully monitored with all the nine GTs. The GTs were of the so-called RADCAL type described previously, whereas the NDs were ordinary fission chambers. The NDs were chosen so that they were located as close as possible to a GT. For the purpose of comparison, the signal of a core-exit thermocouple (assembly J10 in Fig. 3) was also recorded. This core-exit thermocouple was an ordinary K type thermocouple, i.e., chromel/alumel, and was located at the top of a fuel assembly containing a GT, and next to a fuel assembly containing a ND. Such a measurement set-up is summarised in the following Fig. 3.

Regarding the hardware processing of the signals, only the noise content of the NDs and the core-exit thermocouple were monitored by manually offsetting the mean values. These signals were then amplified. No offset and no amplification were applied to the signals of the GTs. These recorded signals were thus digitally converted. The software processing of the signals was carried out via MATLAB [13]. The time-signals were detrended (if a trend was found), and data analysis was performed in the frequency domain. In order to evaluate the APSDs and CPSDs of the different signals, Welch's averaged, modified periodogram method was used. The time-signals were divided into

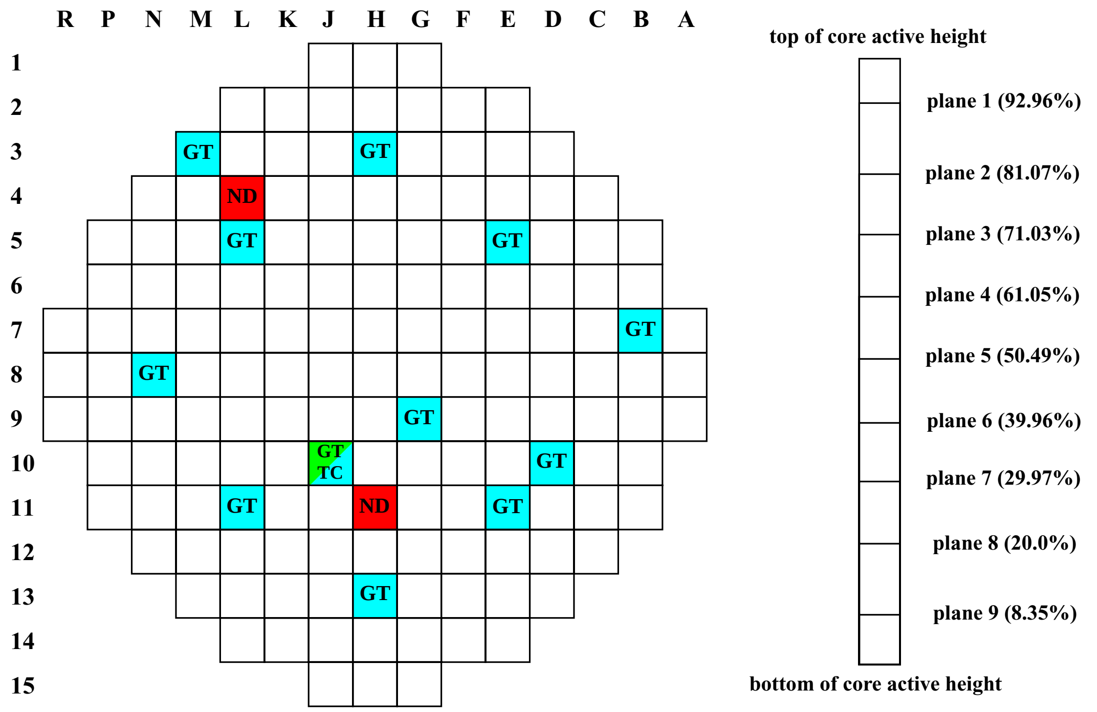

Figure 3. Position of the detectors for the noise measurement in Ringhals-2 on January 16th, 2002 (on the left hand side the radial position on the seventh axial plane; on the right hand side the axial position in the J10 fuel assembly))

overlapping sections of *n* points, then windowed by using a Hanning window. The sections were assumed to overlap by *n*/2 points. As explained in the following, several values for *n* were tested: 512, 256, and 128 points.

4. ANALYSIS OF THE NOISE MEASUREMENT

4.1 SPATIAL STRUCTURE OF THE TEMPERATURE NOISE

The GTs offer an unique opportunity to map the structure of the temperature noise throughout the core, both radially and axially. For that purpose, the APSDs, CPSDs, and coherence of all the available GT signals were calculated. Since the frequency band of interest for the MTC noise estimation is from 0.1 to 1.0 Hz, all the spectra were averaged on that frequency band. Furthermore, the number of points used for the Fast Fourier Transform (FFT) calculations was chosen to be 256 points (this number of FFT points was proven to give better MTC estimations by noise analysis, as will be seen in the following Section 4.2).

The APSD plots are given in Fig. 4. As can be seen on this Figure, the moderator temperature noise is strongly radially heterogeneous in the frequency interval 0.1 - 1.0 Hz. On the other hand, the axial structure of the moderator temperature noise seems to indicate an axial damping of the temperature noise with core elevation. This suggests that the temperature noise is probably created outside the core, most likely at or before the core-inlet. The fact that there is no moderator temperature noise source present inside the core is essential since the MTC noise estimators given by Eqs. (1), (3), and (4) all rely on this assumption. This also means that the axial direction can be completely disregarded while

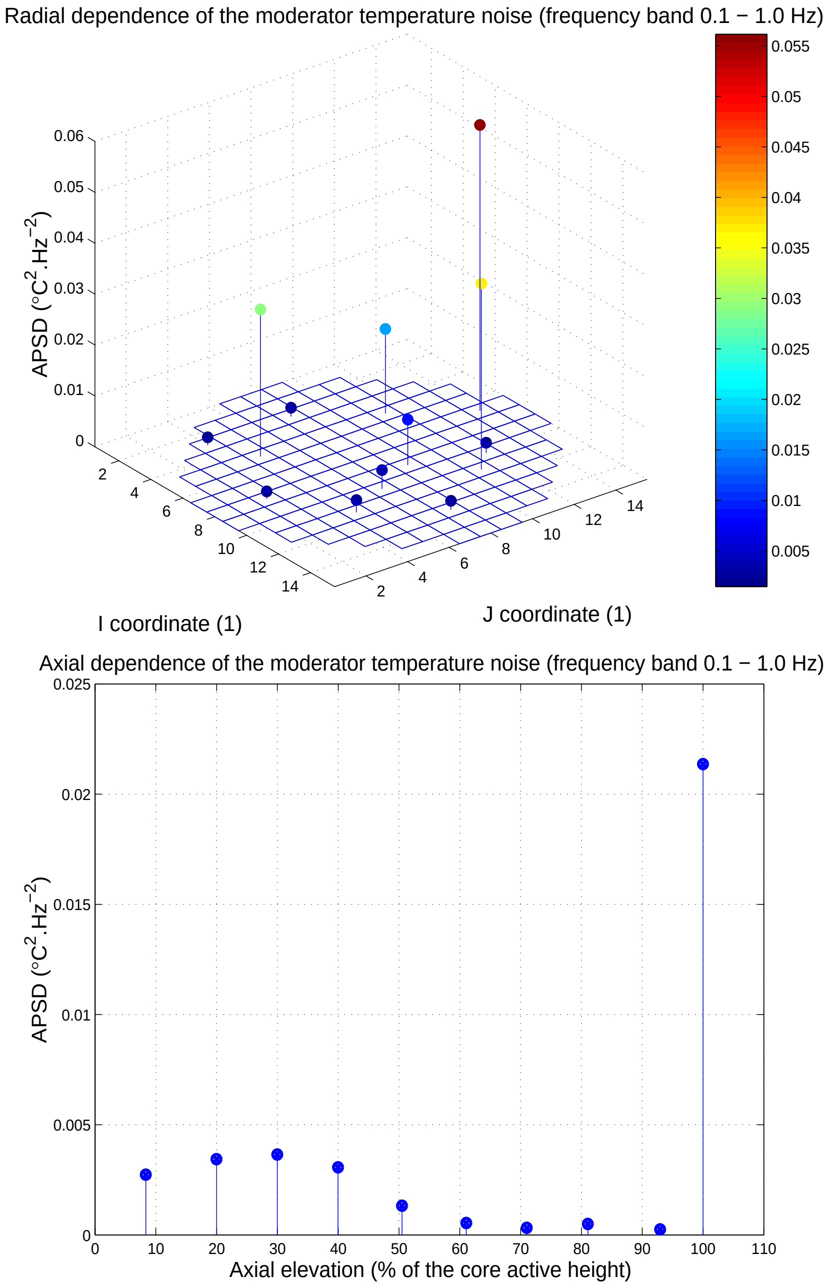

Figure 4. Spatial dependence of the APSD of the moderator temperature noise in the frequency band 0.1 - 1.0 Hz

evaluating the MTC by noise analysis, i.e. the axial dimension has a second-order effect compared to the radial one. Due to the axial damping, it has nevertheless to be noticed that the accuracy of the MTC noise estimation would be probably higher at the bottom of the core, i.e. where the temperature noise is larger, than at the top of the core, i.e. where the temperature noise is damped. Finally, it can be seen that the temperature noise monitored by the core-exit thermocouple (located at the top of the core active height in Fig. 4) is much higher than the temperature noise recorded inside the core. The mixing of the coolant flow above the fuel assemblies is probably responsible for this effect, which is equivalent to the presence of an extraneous noise source. As will be explained in the following, this could be a contributing reason why the MTC was systematically underestimated by using a core-exit TC while evaluating the MTC by the noise analysis technique.

The coherence plots are given in Fig. 5. As can be seen on this Figure, there is practically no radial coherence between the different GTs. On the other hand, the axial coherence is much higher than the radial coherence. Although there is some scattering in the results, one can notice that the axial coherence decreases with increasing distance between two GTs. The damping of the moderator temperature noise travelling upwards is probably responsible for this effect. Regarding the dependence of the CPSD between two detectors with their separation distance depicted in Fig. 6, it could be interesting to try to estimate the correlation length of the moderator temperature noise as defined in

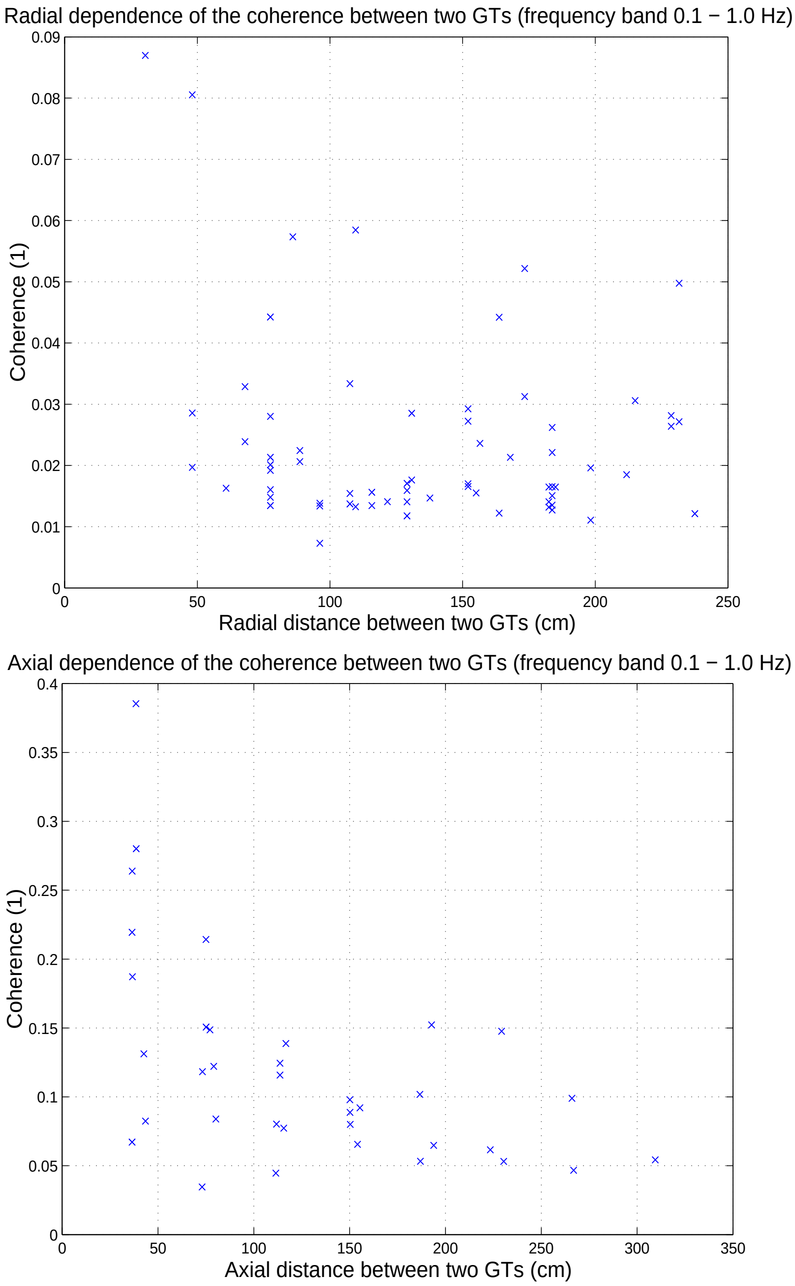

Figure 5. Dependence of the coherence between two GTs with their separation distance in the frequency band 0.1 - 1.0 Hz

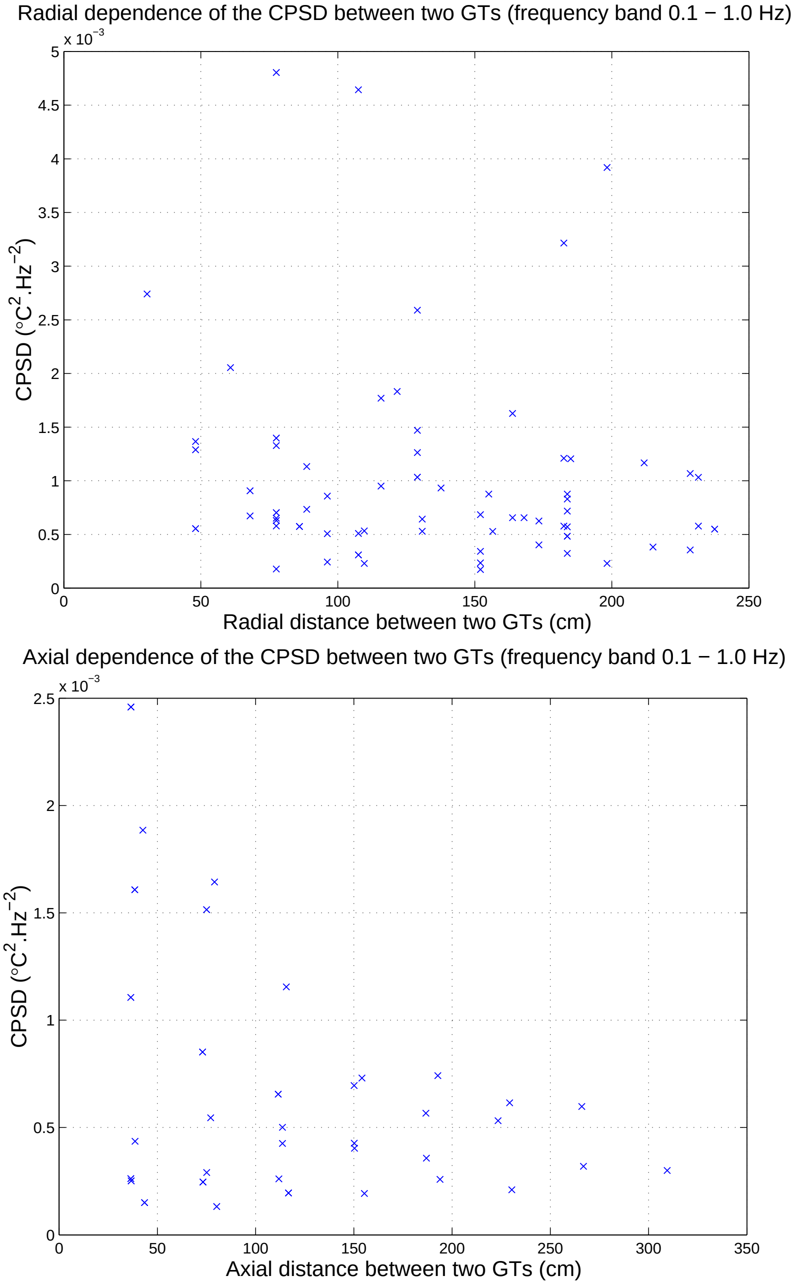

Figure 6. Dependence of the CPSD between two GTs with their separation distance in the frequency band 0.1 - 1.0 Hz

Eq. (6). Unfortunately, such a determination seems to be impossible since one needs to know the full spatial dependence of the APSD of the moderator temperature noise throughout the core (which is the $\sigma^2(\hat{\boldsymbol{r}})$ shape function in Eq. (6)), whereas only the APSD in a few discrete points is actually measured. One can nevertheless clearly see that there is no radial dependence of the CPSD between two GTs with their separation distance. On the other hand, it seems that the CPSD between two GTs depends on their axial separation distance in an exponential manner. It has to be emphasized that the new MTC noise estimator given by Eq. (4) is able to provide a correct MTC estimation whatever the spatial structure of the moderator temperature noise is, i.e. the model given by Eq. (6) being valid or not. Regarding the radial dependence of the CPSD, the correlation length is probably so short that it is not possible to notice it in Fig. 6, where the shortest separation distance between two GTs is roughly 30 cm, i.e.

already too large to see any exponential behaviour. This means that all the points are probably located on the tail of the distribution, thus explaining why there is almost no spatial dependence.

4.2 MTC NOISE ESTIMATIONS

As mentioned previously, the new MTC noise estimator relies on the core-averaged moderator temperature noise:

$$\delta T_m^{ave}(\omega) = \frac{\int \delta T_m(\boldsymbol{r}, \omega) w(\boldsymbol{r}) d\boldsymbol{r}}{\int w(\boldsymbol{r}) d\boldsymbol{r}} \tag{9}$$

where $w(\boldsymbol{r})$ is a weighting function. In this investigation, only the radial structure of the temperature noise is taken into account, since the axial structure is believed to have a second-order effect compared to the radial one (the axial effect is mostly the transport of the temperature noise upwards with the flow, i.e. a damping of the noise for frequencies higher than typically 1 Hz).

Assuming that first-order one-group perturbation theory prevails, the authors showed in [4] that the weighting function that has to be used to calculate the core-averaged temperature noise is the square of the static flux (referenced in the following as the W1 weighting function):

$$w_1(\boldsymbol{r}) = \phi_0^2(\boldsymbol{r}) \tag{10}$$

In this experimental work, the spatial distribution of the static flux throughout the core was obtained from core calculations performed by SIMULATE-3 [14], at the core operating conditions corresponding to the measurement.

Since a good measurement technique should rely on as few as possible calculated parameters, being able to measure the static flux could be particularly interesting. Such a possibility arises with the GTs [15]. The GTs were designed primarily to monitor the static gamma flux in the reactor. It is known that the static gamma flux is directly proportional to the static neutron flux. Since only the static neutron flux relative to its core-averaged value is required in Eq. (9), the knowledge of the corresponding proportionality factor between the static gamma and neutron fluxes is not required[1]. Therefore, a weighting function, which could be used to calculate the core-averaged temperature noise, could be simply the square of the mean value of the GTs (referenced in the following as the W2 weighting function):

$$w_2(\boldsymbol{r}) = [\mathrm{GT\_mean}(\boldsymbol{r})]^2 \tag{11}$$

If one assumes that first-order two-group perturbation theory is applicable, the authors showed in [5] that the weighting function that has to be used to calculate the core-averaged temperature noise is a combination of the direct and the adjoint fluxes, in the fast and thermal groups. If the effect of a change in the moderator temperature is supposed to have the greatest effect on the macroscopic removal cross-

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1. Since the GTs are located within fuel assemblies that have different burnup, the ratio between the static gamma flux and the static neutron flux might be space-dependent. In such a case, the space-dependence has to be taken into account in the evaluation of the core-averaged temperature noise. Preliminary CASMO-4 [16] modelling of a single typical PWR assembly at different burnup showed that the standard deviation of the ratio between the static gamma and neutron fluxes is less than 10% of the average value for burnup up to 60 GWd/tHM. In the case of a full core, this figure is probably lower since a GT is sensitive to the gamma flux of several neighbouring fuel assemblies with different burnup. From one GT location to another, the average burnup of the fuel assemblies that the GT is sensing is roughly the same, due to the reloading pattern. Further investigation is nevertheless needed and is currently under way.

section, one obtains the following weighting function (referenced in the following as the W3 weighting function):

$$w_3(\boldsymbol{r}) = [\phi_1^+(\boldsymbol{r})\phi_1(\boldsymbol{r}) - \phi_2^+(\boldsymbol{r})\phi_1(\boldsymbol{r})] \quad (12)$$

If the greatest effect induced by a change of the moderator temperature is the effect on the macroscopic thermal absorption cross-section, then the weighting function is (referenced in the following as the W4 weighting function):

$$w_4(\boldsymbol{r}) = -\phi_2^+(\boldsymbol{r})\phi_2(\boldsymbol{r}) \quad (13)$$

These different weighting functions were tested by using the new MTC noise estimator given by Eq. (4). For the purpose of comparisons, the traditional MTC noise estimator given by Eq. (1) was also evaluated. In the latter case, the local temperature noise was used, recorded either inside the core via the closest GT to the ND, or outside the core via the core-exit TC. All the MTC estimations were therefore carried out for both of the in-core neutron detectors H11 and L04. The point-kinetic parameters of the core, i.e. the effective fraction of delayed neutrons, the prompt neutron lifetime, and the one-group precursors decay constant, which are required in the MTC noise estimators, were estimated by SIMULATE-3 to be equal to 537 pcm, 22 μs, and 85 ms respectively. The MTC was also directly evaluated by SIMULATE-3 and was found to be equal to -51 pcm/°C. This value was considered as the reference value in the rest of this study.

The MTC noise evaluations showed that the MTC was frequency dependent with rather huge variation of the MTC magnitude in the frequency range 0.1 - 1.0 Hz. Therefore the following methodology was applied. In this frequency range, the maximum of the coherence between the ND and the temperature noise (estimated either from the W1, W2, W3, or W4 weighting functions, or directly from the GT J10, the GT L05, or the core-exit thermocouple) was first determined. Then all the frequencies for which the coherence was larger than half this maximum were used for the MTC evaluation. The final MTC value was simply obtained by averaging these values at the corresponding frequencies.

It was found that the MTC estimated via the previous procedure was strongly dependent on the number of points used for the Fast-Fourier Transform (FFT). Such dependence can be seen in Figs. 7 and 8, where the W2 weighting function was used for the calculations (since this weighting function is the most practical one to use from a measurement viewpoint). In these Figures, the points used for the final MTC evaluation are circled in bold.

The resulting MTC values are depicted in Fig. 9, where the standard deviation associated with each MTC evaluation is also represented. As can be seen on this Figure, the 256 FFT points evaluation seems to be the most realistic one, both with respect to the reference MTC value given by SIMULATE-3 and to the relatively flat behaviour of the MTC for the selected frequencies (the peaks in the 512 FFT points MTCs are clearly non-realistic). Assuming therefore that the spectral analysis of the signals has to be carried out with 256 FFT points, one can compare the MTCs given by the different noise estimators and the different weighting functions. Such a comparison can be seen in Fig. 10, where the standard deviation associated with each MTC estimation is also represented.

The main conclusion from this MTC noise measurement is that using the new MTC noise estimator given by Eq. (4) gives a MTC value that is very close to the reference value given by SIMULATE-3, if one takes the confidence intervals into account. This new MTC noise estimator relies on the core-averaged moderator temperature noise, which can be evaluated in different ways (by using either the W1, the W2, the W3, or the W4 weighting functions). As Fig. 10 shows, if one uses the core-exit TC located above the fuel assembly J10, and consequently uses the traditional MTC noise estimator given by Eq. (1), then the MTC is strongly underestimated by a factor of approximately 10. Likewise,

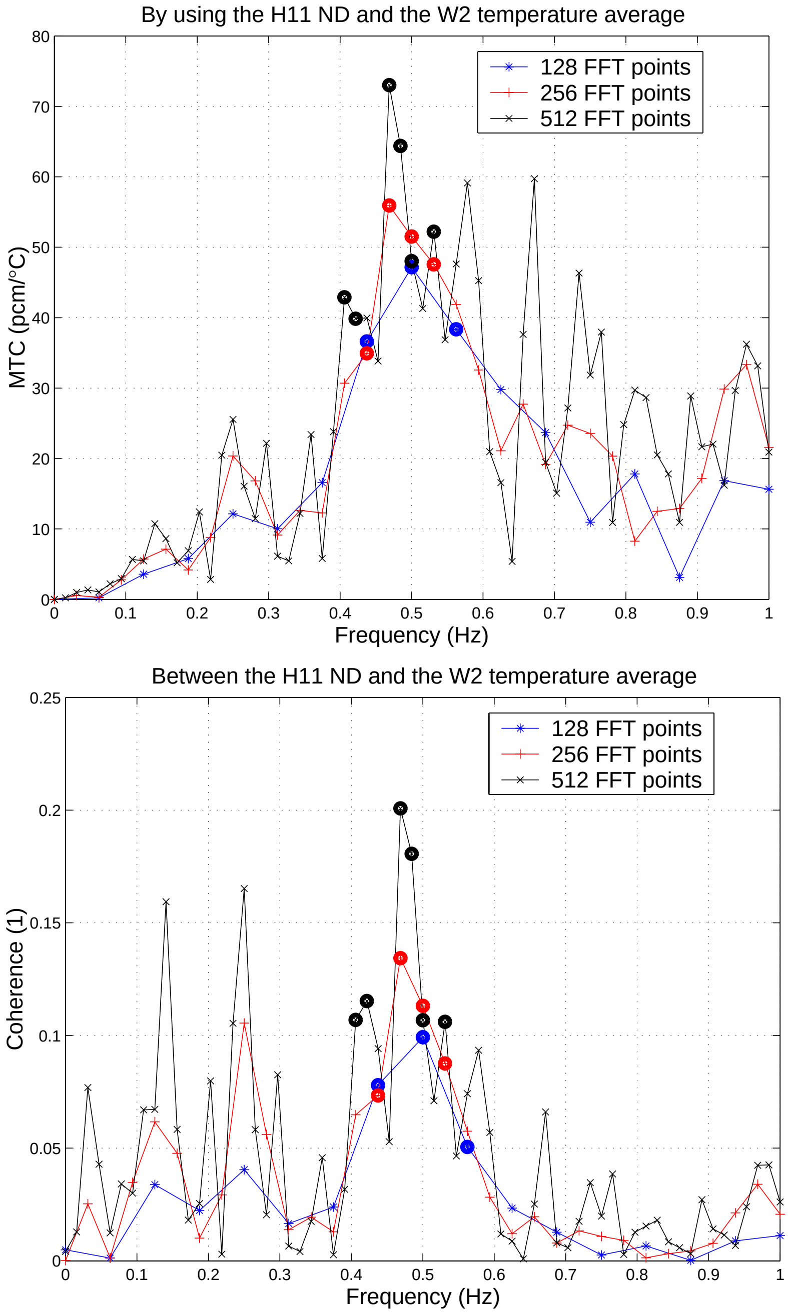

Figure 7. Frequency dependence of the MTC noise estimation with respect to the number of FFT points used (neutron noise measured in the H11 assembly and temperature noise evaluated by using W2)

replacing the core-exit TC by a single GT (the nearest one to the ND used in the evaluation) systematically underestimates the MTC value by a factor of 3 to 5. The reason why the MTC is underestimated at the core-exit is that the temperature fluctuations are larger at the core-exit than inside the core. Similarly, the fact that the MTC is still underestimated when using one single GT instead of using all the signals of the GTs and the corresponding core-averaged temperature noise means that the temperature noise recorded in this specific point of the reactor is larger than the core-averaged one. The underestimation of the MTC by using one single temperature detector (either the core-exit TC or a GT) can be directly seen on Fig. 11, which shows the square root of the ratio between the APSD of the

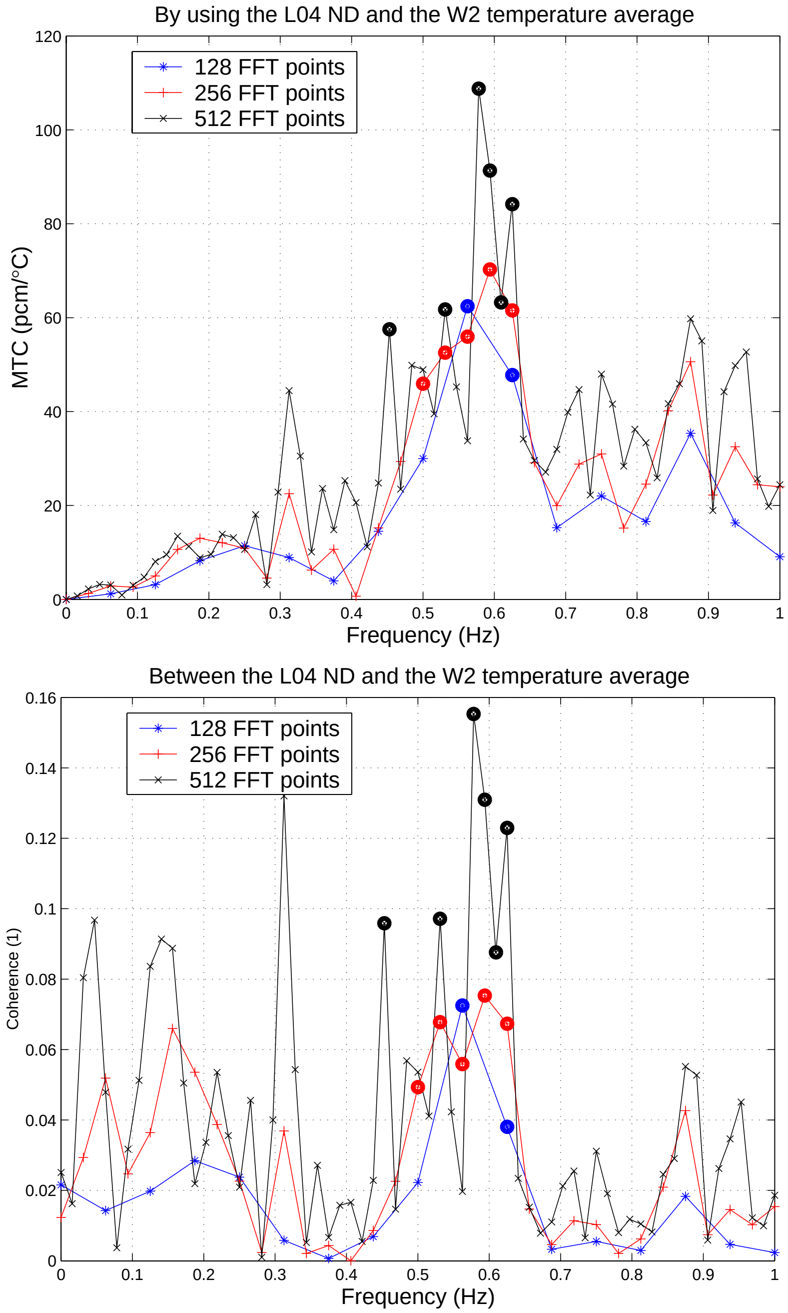

Figure 8. Frequency dependence of the MTC noise estimation with respect to the number of FFT points used (neutron noise measured in the L04 assembly and temperature noise evaluated by using W2)

average temperature and the APSD of one in-core GT and that of the core-exit thermocouple, respectively. By virtue of the Wiener Khinchin theorem, this square root represents actually the ratio between the traditional and the new MTC noise estimators as follows:

$$\sqrt{\frac{APSD_{\delta T_m^{ave}}(\omega)}{APSD_{\delta T_m}(\boldsymbol{r},\omega)}} \approx \left|\frac{\delta T_m^{ave}(\omega)}{\delta T_m(\boldsymbol{r},\omega)}\right| \approx \left|\frac{H_1^{biased}(\boldsymbol{r},\omega)}{\tilde{H}_1^{biased}(\boldsymbol{r},\omega)}\right| \tag{14}$$

As Fig. 11 shows, the square roots are both smaller than unity and, interestingly, quite flat in the

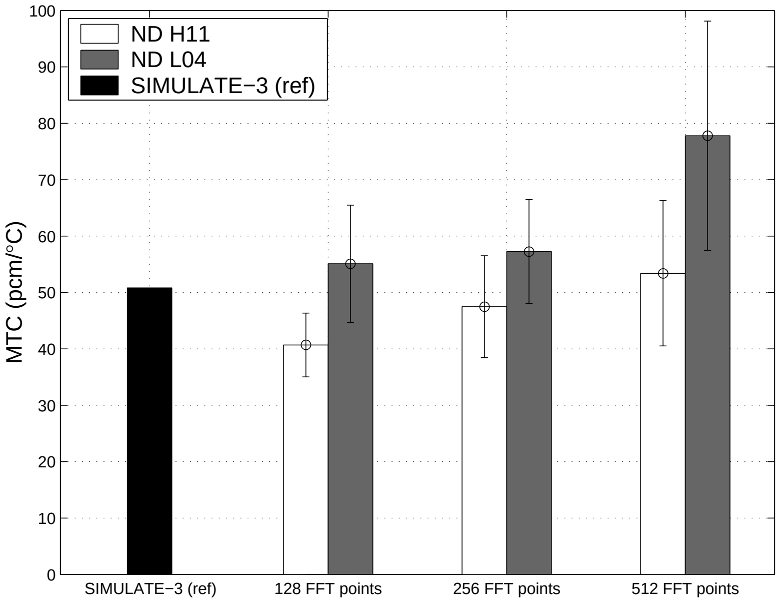

Figure 9. Comparison of the MTC noise evaluations with respect to the number of FFT points used (temperature noise evaluated by using W2)

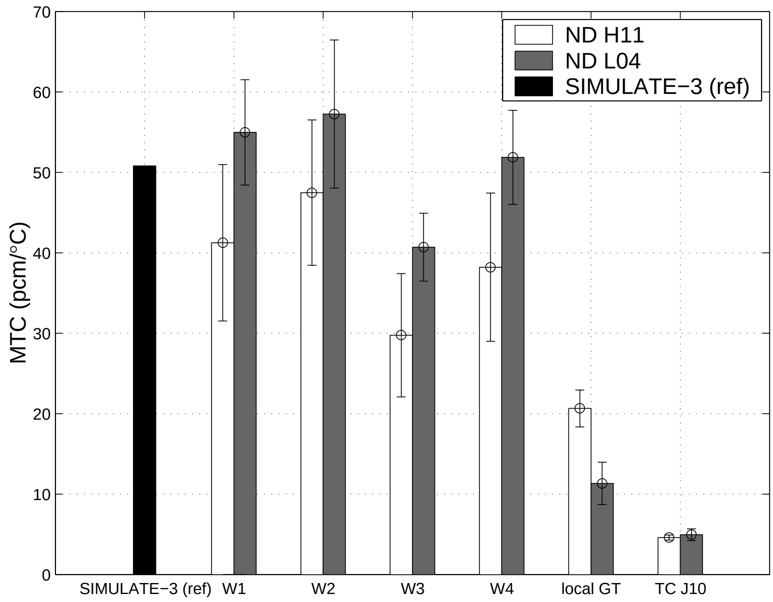

Figure 10. Comparison between the different MTC noise estimators (estimations carried out with 256 FFT points)

frequency range 0.1-1.0 Hz. The main reason of the MTC underestimation in all the experimental work so far is therefore the overestimation of the temperature noise outside the core. But using a single in-core thermocouple, i.e. a GT in the case of Ringhals-2, does not provide either the actual MTC value, since the temperature noise appears to be radially loosely coupled in the core. On the other hand, using the core-averaged moderator temperature noise gives the correct MTC value.

The fact that the results using the core-averaged temperature noise do not depend strongly on the radial position of the ND used in the MTC evaluation and give the actual MTC value suggests that the

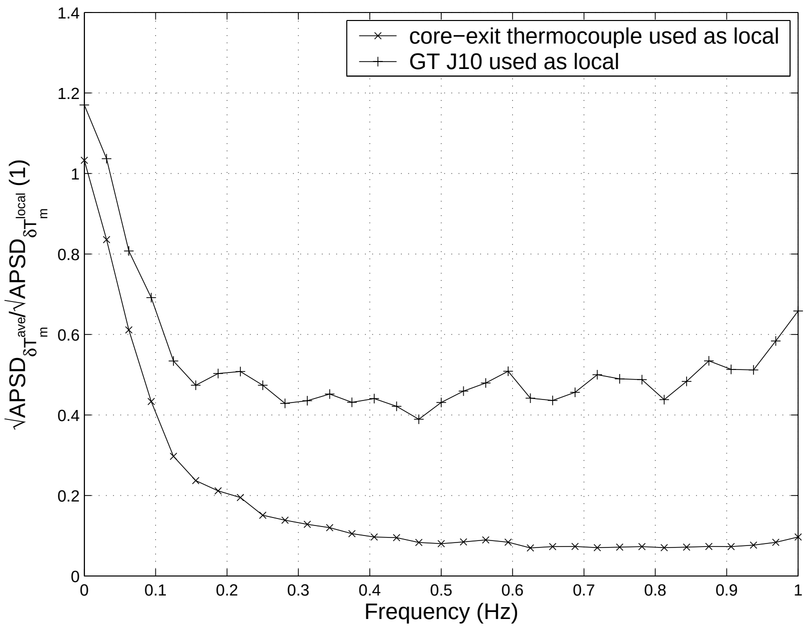

Figure 11. Comparison between the noise levels recorded by the core-exit thermocouple, a GT, and the planar average of all the GTs

deviation of the reactor response from point-kinetics does not play a significant role on the MTC estimation by noise analysis (the new MTC noise estimator given by Eq. (4) still assumes a point-kinetic behaviour of the reactor). This effect was expected from the theoretical work performed previously and briefly recalled in Section 2.3. Consequently, the conclusions drawn by this theoretical work are proven by the experimental one: the main reason of the MTC underestimation by noise analysis in all the experimental investigations performed until now lies with the fact that the moderator temperature noise is radially strongly heterogeneous in the core; the resulting deviation of the reactor response from point-kinetics is nevertheless not significant.

As can be seen on Fig. 9 and on Figs. 7 and 8, the MTC evaluation by using 256 FFT points seems to give the most realistic results. Taking the standard deviation into account gives an MTC estimated by SIMULATE-3 lying in the confidence interval of the measurement. The way the final MTC is calculated, i.e. detecting the frequency having the highest coherence and taking all the frequencies between 0.1 and 1.0 Hz having a coherence higher than half this maximum into account, is very subjective. Having a more restrictive way of choosing the frequencies for the final MTC evaluation would narrow the confidence interval and give a better MTC estimation.

As can be seen on Fig. 10, the MTC depends to some extent on the weighting function used to calculate the core-averaged temperature noise throughout the core. The weighting functions using the square of the static flux, either calculated by SIMULATE-3 (W1) or measured via the GTs (W2), give the best results. The W3 weighting function gives somewhat underestimated MTC values (but still much higher than using a single GT or a single TC), whereas the W4 weighting function gives also acceptable results. This means that the hypothesis on which the W4 weighting function was derived is better than the one on which the W3 weighting function was derived, i.e. the moderator temperature noise has a bigger effect on the macroscopic thermal absorption cross-section than the removal cross-section with respect to the MTC.

Using the W2 weighting function has many practical aspects, the most important one being that the static flux does not need to be calculated but can be directly measured via the GTs. The GTs are therefore very versatile tools since they can provide both the moderator temperature noise and the static neutron flux throughout the core. These are required for an accurate estimation of the core-averaged moderator temperature noise. This core average can then be used in the new MTC noise estimator that was proven, both theoretically and experimentally, to give an accurate MTC estimation, wherever the neutron noise is measured in the core. The only parameters that are needed for the MTC estimation are the effective fraction of delayed neutrons, the prompt neutron lifetime, and the one-group precursors decay constant, which can be easily predicted by any static core simulator.

5. CONCLUSIONS

In this paper, it was shown both theoretically and practically in the Swedish Ringhals-2 PWR that the main reason of the MTC underestimation by noise analysis is due to the fact that the moderator temperature noise is strongly radially heterogeneous. Therefore measuring the moderator temperature noise in one single point of the reactor, such as for instance at the core-exit with the traditional MTC noise estimator, cannot provide the expected MTC value since the core-averaged temperature noise, on which the MTC definition relies, is different from the local temperature noise. Regarding the axial dependence of the moderator temperature noise, it was noticed that only a damping effect of the noise existed, thus suggesting that only the radial structure of the moderator temperature noise has to be taken into account. This was done via the use of a new MTC noise estimator that relies on the radial average moderator temperature noise. This new MTC noise estimator was proven to give the expected MTC value, wherever the neutron noise is measured in the reactor. This indicates also that the deviation of the reactor response from point-kinetics is negligible, since this new MTC noise estimator still assumes a point-kinetic behaviour of the reactor.

The analysis of the spatial structure of the moderator temperature noise was carried out with GTs, which are permanently installed in the Swedish Ringhals-2 PWR. The GTs are very versatile tools since they can provide both the moderator temperature noise in the frequency range 0.1 - 1.0 Hz and the spatial structure of the neutron flux. Both of them are required to estimate the core-averaged moderator temperature noise, on which the new MTC noise estimator relies. This means that the only parameters that need to be estimated by core calculations for the MTC measurement by noise analysis are the ones necessary to estimate the zero-power reactor transfer function. In the frequency band of interest for the MTC estimation by noise analysis, this open-loop reactor transfer function can be rather well approximated simply by the reciprocal of the effective fraction of delayed neutrons, which is therefore the only parameter that needs to be estimated by core calculations. Such an estimation is usually very accurate with today's static reactor codes.

Although this noise measurement is very encouraging, more work needs to be done. More specifically, a few points have to be investigated in further detail, such as for instance the frequency dependence of the MTC in the frequency range 0.1 - 1.0 Hz. Likewise, the effect of estimating the core-averaged moderator temperature noise by using several axial planes containing the GTs (only one axial plane was taken into consideration in this study) has also to be investigated. Regarding the measurement itself, it was found that the noise signals of the GTs were not accurate enough. Manually offsetting the mean value of the GTs seems to be necessary before the analogue-to-digital conversion.

More measurements are planned in the future in order to verify the reproducibility of these results.

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NOMENCLATURE

APSD	Auto-Power Spectral Density
BOC	Beginning Of Cycle
CPSD	Cross-Power Spectral Density
EOC	End Of Cycle
FFT	Fast Fourier Transform
GT	Gamma-Thermometer
HFP	Hot Full Power
HZP	Hot Zero Power
MOX	Mixed Oxide
MTC	Moderator Temperature Coefficient
ND	Neutron Detector
PWR	Pressurised Water Reactor
TC	Thermocouple

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