Note:
This is a translation of the document entitled “DWR-Neutronenflussschwankungen”.
In case of discrepancies between the English translation and the German original, the original shall prevail.

RSK Statement
(457th meeting on 11.04.2013)

PWR neutron flux oscillations

CONTENTS

1 Background

The Federal Ministry for the Environment (BMU) requested the Reactor Safety Commission (RSK) by letter dated 06.07.2011 [1] together with a supplementary report of the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) [2] to prepare a statement on neutron flux oscillations resp. neutron flux noise (for explanation of terms, see Chapter 3) in pressurised water reactors (PWRs). The background to this request for advice is the increase in the amplitude of the neutron flux oscillations in PWR plants that has been observed for several years now. The RSK was asked to address the following topics:

1) Clarification of possible causes for increasing neutron flux oscillation amplitudes,

2) assessment of the safety significance of such neutron flux oscillation amplitudes, and

3) assessment of I&C measures used for filtering of neutron flux signals.

At its 439th meeting on 07.07.2011, the RSK commissioned the RSK Committee on REACTOR OPERATION (RB) to consult on this topic. In addition, the RSK Committee on ELECTRIC INSTALLATIONS (EE) and some members of the RSK Committee on PLANT AND SYSTEMS ENGINEERING (AST) joined the consultations due to the cross-cutting nature of the topic.

2 Consultations

At its 204th meeting on 27.07.2011, the RSK Committee RB thus adopted a corresponding concept for the consultations. In addition, the RSK Committee EE was asked for a safety assessment on neutron flux filters currently used in the plants. At the 209th RB meeting on 23.02.2012, VGB PowerTech e.V. (VGB) reported to the Committee and members consulted of the Committees AST and EE about the status and development regarding neutron flux oscillations in the PWR plants [3]. Subsequently, the Committee RB formulated first recommendations in response to the issues raised in the BMU’s request for advice [1] and asked the VGB to report back on new findings after a one-year period. In continuation of its consultations, the Committee RB solicited report on the results of the analysis of the neutron flux signals of a PWR (“*Analyse der Neutronenflusssignale eines DWR*”) [4] from the Institute for Safety Technology (ISTec) GmbH at its 213th meeting on 11.10.2012. The reporting comprised, among other things, the presentation of results of comparative studies according to [2] in extracts. Meanwhile, at its 225th meeting on 30.01.2013, the RSK Committee EE has adopted a presentation of the consultation results with respect to the filters currently used and forwarded it to the Committee RB for further consultations [5]. At the 216th meeting on 28.02.2013 of the RSK Committee RB, the VGB PowerTech reported on the status and development regarding neutron flux noise and the new findings on this issue [6]. Moreover, at the same meeting, the TÜV NORD EnSys was heard on the results of its analyses of the causes of neutron flux noise on behalf of the Lower Saxony Ministry for the Environment, Energy and Climate Protection (NMU) [7]. The 217th RB meeting on 14.03.2013 served to finalise the draft statement. The draft statement was adopted at the 218th Committee meeting on 04.04.2013. The RSK discussed and adopted the draft statement of the RSK Committee on REACTOR OPERATION (RB) at its 457th meeting on 11.04.2013.

3 Terms and explanations

PWR neutron flux noise

The neutron flux noise in PWR plants is caused by interactions between the moderator, fuel, absorbers and neutron flux. These may be due, among other things, to temperature and density fluctuations in the primary coolant. In this statement, the term neutron flux noise is understood as the neutron flux oscillations observed during power operation in the frequency range of up to about 1 Hz.

Measurement and processing of neutron flux signals in PWR plants

The neutron flux signals continuously measured by the instrumentation of a PWR inside the core (in-core) and outside the core (ex-core) are processed in the reactor protection system, in the reactor power limitation system and, in the lower power range, also in the reactor power control system. In order to monitor the local power distribution inside the core, in-core detectors are used. However, regarding the issue of actuation of the reactor power limitation of the reactor protection, only the signals from the ex-core instrumentation are of relevance, as explained below.

Determination of reactor power in PWR plants

For determining the full-core power distribution, the signals from the ex-core detectors are used. The continuous determination of the thermal reactor power is mainly based on the measurement of the heat-up ranges in the four loops of the primary circuit. Since this signal follows a change in the reactor core power only very slowly, this signal is corrected with the change of the ex-core neutron flux signal. Since, in contrast to the hydraulic parameters, the neutron flux signals follow the current reactor power quasi promptly, the combination of both signal types results in the short-term corrected thermal reactor power Short-term oscillations in the neutron flux signal thus also lead to short-term oscillations in the short-term corrected thermal power, which is further processed as an entry signal in the reactor power limitation system and the reactor protection system.

4 Assessment criteria

Increased neutron flux oscillations must not lead to undue impacts on safety. In this respect, the requirements laid down in the nuclear regulations established for normal operation, transients and accidents are to be applied for the reactor core design and its monitoring.

5 Current situation and consultation results

In connection with the core loadings modified since the nineties, increased neutron flux noise has been observed, among other things. The increased neutron flux noise levels are, among others, accompanied by the change of the moderator temperature coefficient (MTC) due to increases of fuel enrichment.

A further significant increase in the noise amplitude has been recorded since 2001, where the increase observed there no longer correlates with an increase of the MTC. The reasons for this increase have not been clearly identified yet. In some plants, the increased neutron flux noise led to more frequent activation of the reactor power limitation systems and, in one plant, also to the activation of the reactor protection system.

In most plants, the increase of the noise amplitude continued until about 2009 and, since then, further increase has not been observed according to [6]. In response to this development, the German PWR plants have already been equipped with neutron flux signal filters starting in the 80s. Currently, due to the noise superimposing the average value, short-term corrected thermal power values temporarily occur in some plants that reach the activation levels of the reactor power limitation system despite the noise filtering, especially towards the end of the operating cycle.

For many years, ISTec has been regularly performing measurements and evaluations of vibration and neutron flux signals in the area of the reactor cores in some PWR plants. The results and findings gained by it were summarised in a brief assessment by GRS on behalf of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) [2]. The statements contained therein are essentially consistent with this statement. Moreover, it contains suggestions regarding further studies to clarify the causes of the increased neutron flux noise.

After consultation and evaluation of the information available, the RSK arrived at the following conclusions concerning the current situation and the following assessments:

- According to the VGB [3] and ISTec [2, 4], until about ten years ago, the noise amplitudes for PWR plants with steam generators (SGs) without preheater reached values of about +/- 1 % and in the PWR plants with SGs with preheater about +/- 3 to +/- 4 % of the average value of the neutron flux signal. Since then, the noise amplitudes have approximately doubled and currently reach, in the case of the SGs with preheater, about +/- 8 % to +/- 10 %. With these noise amplitudes, the short-term corrected thermal power will be in the range of the activation of the reactor power limitation system even after filtering of the neutron flux signal.

- That plants with SGs with preheater and core support structure (Grafenrheinfeld NPP (KKG), Grohnde NPP (KWG) and Brokdorf NPP (KBR)) show higher neutron flux noise amplitudes than plants with SGs without preheater and with a flow skirt for flow equalisation and homogenisation at the coolant inlet can be explained by the formation of temperature streaks in the cold leg of the primary coolant which are due to the reactor type design. For SGs with preheater, the temperature differences between the temperature streaks in the primary coolant are greater than in SGs without preheater. This supports the hypothesis that the temperature differences between the streaks have a significant influence on the neutron flux noise.

- A known and explicable behaviour of a PWR reactor core is the increase of the neutron flux noise in the course of an operating cycle due to the absolutely increasing moderator temperature coefficient resulting from the changing isotopic composition of the fuel and the reduction of boric acid concentration in the coolant. However, the increase of the neutron flux noise observed since about 2001 can no longer be explained with the increase of the MTC alone [3].

- Apart from the changes in the reactor core in recent years, no significant changes were made e.g. to components of the reactor coolant system which might explain this increase of the neutron flux noise. It can therefore be assumed that it is due to influences inside the reactor cores. In recent years, the core loading with higher-enriched fuel assemblies (FAs) increased which tends to result in more inhomogeneous power distributions. Furthermore, new FA designs were introduced, e.g. with modified spacers. There are no substantiated findings so far as regards which of these changes in the reactor core contribute to the increased neutron flux noise, which can no longer be explained with a more negative value of the MTC. According to [7], there are indications that this increase could correlate with the introduction of new FA designs (e.g. as a result of modified spacer designs).

- According to [7] the impacts of the increased noise amplitudes are checked and evaluated in respect of their safety significance for each cycle.

- According to [6], modern core simulators are able also to consider the influence of the core composition, burnup and enrichment distribution, and the fuel types in the visual range of the detectors for an accurate cycle-specific prediction of the noise amplitudes.

6 Statements on the topics of the BMU's request for advice and recommendations

Taking into account the current state of knowledge, the RSK's statements on the topics of the advisory request are as follows:

6.1 Clarification of possible causes for increasing neutron flux oscillation amplitudes

The causes of the increase of the neutron flux noise amplitudes in recent years have not been sufficiently clarified yet. Besides the known moderator temperature coefficient there are different possible explanations for the additive increase of the neutron flux noise. For example, changed FA designs are assumed to be the cause [7] for a change of mechanical vibrations in the core and for changes in the axial coolant transport behaviour (due to modified spacer designs). This approach is supported by similar operating experiences in two WWER1000 plants in the 1990s. However, the resulting impacts on the neutron flux noise could not be explained in detail yet.

This situation is not satisfactory with regard to the knowledge on the causes for the increase of the neutron flux noise amplitudes. The RSK holds the view that the causes and mechanisms of the neutron flux noise should be understood to the extent that all relevant influencing factors can be explained and quantitatively limited such that these can be considered in the reactor core design. The RSK therefore recommends intensifying the activities to determine the causes and, in this context in particular, a closer exchange of information of all institutions already involved (manufacturers, operators, experts, research institutions) to investigate the contributing factors. One of the possibilities to gain clarifying information on the observed behaviour of the neutron flux noise is an in-depth evaluation of measured data, their correlations among each other and between integral and local changes to the reactor cores.

Furthermore, annual reports on the development of the noise, on any corrective measures taken, and on the progress made in explaining the causes of the neutron flux noise should be submitted to the RSK until the causes have been clarified. In this context, the state of development of the core simulator programs used to predict the noise amplitudes should also be reported on.

6.2 Assessment of the safety significance of neutron flux oscillations

According to the RSK, four aspects are to be considered regarding the safety significance. The first concerns the integrity of the fuel rods during normal operation, the second is the impact on the heat transfer conditions (DNB), the third is the impact on the fuel, and the fourth is the frequent activation of reactor power limitation measures.

Integrity of the fuel rods during normal operation

Regarding the integrity of the fuel rods, there are no indications from operating experience so far that the increased noise has led to an increase of FA damages. The observed neutron flux oscillations are damped by the much higher time constant of heat transfer from the fuel to the cladding tube and into the primary coolant so that, according to current knowledge, no temperature fluctuations are to be expected at the cladding tube resulting from the neutron flux noise that are relevant for the integrity of the cladding tubes.

Heat transfer conditions during transients

The neutron flux oscillations are accompanied by temperature variations in the fuel. According to first estimates, these temperature variations are in the range < 10 K (peak to peak). The RSK recommends that the impact of the neutron flux noise and the associated temperature fluctuations in the fuel on the conditions of the heat transfer to the coolant should be assessed with regard to the determination of the DNB margin.

Impacts on the fuel
The RSK recommends assessing the impact of the neutron flux noise and the associated temperature fluctuations on a potentially accelerated fine fragmentation of the fuel.

Frequent activation of reactor power limitation measures
At some plants, the noise amplitudes superimposed on the average values of the neutron flux signals led to a frequent one- and multi-channel triggering of the reactor power limitation system by reaching the limit values.

From a safety point of view, a multi-channel activation of limitation measures is covered by the plant design, but a frequent activation of measures of level of defence 2 (reactor power limitation measures) during normal operation should generally be avoided according to the defence-in-depth concept. A noise-induced activation of reactor power limitation measures should generally be avoided since, in the opinion of the RSK, the frequent activation of reactor power limitation measures may lead to the disadvantageous effect that the control room staff gets used to it. Getting used to a noise-induced activation may have the effect of "overlooking" the activation of reactor power limitation for other reasons. The RSK therefore recommends minimising a multiple noise-induced activation of limitation measures through a cycle-accompanying monitoring of the neutron flux noise and, if necessary, by the initiation of measures in due time.

From the RSK's view, the systematic noise-induced activation of limitation measures should generally be avoided, but activation of the limitation measures five times per month can be tolerated.

6.3 Assessment of I&C measures used in the plants for filtering of neutron flux signals

Neutron flux signal filters are used in all PWR plants. The filter characteristics and their potential impacts were assessed in detail in [4].

The delays of the neutron flux signals due to the respective filter behaviour and the resulting changed activation behaviour of safety functions are to be considered conservatively in the relevant safety demonstrations (in particular as regards transient calculations). The RSK holds the view that in case of compliance with this requirement there will be no restriction for processing the neutron flux measurement signals in the reactor protection and in the reactor power limitation appropriately.

Currently, maximum dead ranges are specified for the facilities still in operation. The RSK recommends not using dead range settings higher than ± 10 % of the nominal reactor power to smooth the neutron flux signals until the causes have been clarified.

Summary of recommendations:

1. The RSK recommends intensifying the activities to determine the causes and, in this context in particular, a closer exchange of information of all institutions already involved (manufacturers, operators, experts, research institutions) in order to investigate the contributing factors. One of the possibilities to gain clarifying information on the observed behaviour of the neutron flux noise is an in-depth evaluation of measured data, their correlations among each other and between integral and local changes to the reactor cores.

2. The RSK recommends that the impact of the neutron flux noise and the associated temperature fluctuations in the fuel on the conditions of the heat transfer to the coolant should be assessed with regard to the determination of the DNB margin.

3. The RSK recommends assessing the impact of the neutron flux noise and the associated temperature fluctuations on a potentially accelerated fine fragmentation of the fuel.

4. From the RSK's view, the systematic noise-induced activation of limitation measures should generally be avoided. The RSK therefore recommends minimising a multiple noise-induced activation of limitation measures through a cycle-accompanying monitoring of the neutron flux noise and, if necessary, by the initiation of measures in due time. However, the RSK considers activation of the limitation measures five times a month to be tolerable.

5. The delays of the neutron flux signals due to the respective filter behaviour and the resulting changed activation behaviour of safety functions are to be considered conservatively in the relevant safety demonstrations (in particular as regards transient calculations).

6. Until the causes of increased noise amplitudes have been clarified, no dead ranges higher than the current maximum dead ranges specified (± 10 % P_n) should be set in the neutron flux signal filters.

7. Until final clarification of the causes of that share of the increased neutron flux noise that cannot be explained with the variation of the moderator temperature coefficient, the RSK asks to submit annual reports containing at least the following information:

   - Further development of the unfiltered neutron flux noise.

- The maximum dead ranges set in the filters per cycle.

- Measures taken and progress made in explaining the causes of the increased neutron flux noise and presentation of the results. In this context, the state of development of the core simulator programs used to predict the noise amplitudes should also be reported on.

- Results of the assessments regarding the temperature fluctuations at the cladding tube and in the fuel induced by the neutron flux noise.

- Description of corrective measures taken and assessment of measures introduced to reduce the neutron flux noise amplitudes (e.g. changes in the fuel assembly design, in the loadings). Presentation of the results, including explanation why the measures taken will not cause any other adverse effects with regard to safety.

- Triggering frequency by reaching the limit value 14 or the local power reduction limit value of the reactor power limitation system in the past operating cycles.

7 References

[1] BMU Beratungsauftrag “Neutronenflussschwankungen”, 06.07.2011

[2] GRS Stellungnahme neutron flux noise V09-1 im Rahmen des BMU Vorhabens 3609R01321 “Vertiefte Untersuchungen von Betriebserfahrungen aus Kernreaktoren – Teil B: Fachberatungen”, 21.02.2011

[3] Präsentation der VGB PowerTech e. V. in der 209. Sitzung des RSK-Ausschusses REAKTORBETRIEB (RB), 23.02.2011, Vortragsfolien

[4] Präsentation des Instituts für Sicherheitstechnologie GmbH (ISTec) in der 213. Sitzung des RSK-Ausschusses REAKTORBETRIEB (RB), 11.10.2012, Vortragsfolien

[5] Anlage 1 zum Ergebnisprotokoll der 225. Sitzung des Ausschusses ELEKTRISCHE EINRICHTUNGEN, 30.01.2013 “DWR Neutronenflussschwankungen” Filtereinrichtungen

[6] Präsentation der VGB PowerTech e. V. in der 216. Sitzung des RSK-Ausschusses REAKTORBETRIEB (RB), 28.02.2013, Vortragsfolien

[7] Präsentation der TÜV NORD EnSys Hannover GmbH & Co. KG in der 216. Sitzung des RSK-Ausschusses REAKTORBETRIEB (RB), 28.02.2013, Vortragsfolien