IN-CORE MEASUREMENTS OF REACTORS INTERNALS VIBRATIONS BY USE OF ACCELEROMETERS AND NEUTRON DETECTORS

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Abstract

A miniature biaxial accelerometer was developed for vibration measurements in radioactive environments. The sensor is small enough to be assembled in Self-powered Neutron Detector (SPND) in-core instrument strings of PWRs or to be inserted into the travelling in-core probe system of BWRs. Two accelerometers were installed inside of the core of an operating power reactor (PWR, 350 MW_{el}). The vibrations of different components as fuel assemblies, reactor pressure vessel / core barrel and the in-core instrument string / instrument tube system were measured in frequency and amplitude during normal reactor operation by use of these accelerometers and by use of SPNDs. Neutron-mechanical scale factors were determined. The displacements of vibrating reactor components which cannot be measured by other means during normal reactor operation can be determined through the scale factors from the neutron spectra of signals measured by the standard in-core neutron instrumentation.

A full scale model of a BWR Travelling In-core Probe (TIP) system was constructed for testing the displacement feasibility and coupling of the accelerometer inside of a 42 m long tube. In the near future one in-core accelerometer will be inserted into the TIP-system of an operating 1300 MW_{el} BWR in order to investigate the vibration of BWR internals, especially those of the instrument tubes itself, qualitatively and quantitatively and to determine the corresponding neutron-mechanical scale factors.

Introduction

The vibration of the different internals of a reactor can be monitored using neutron noise analysis. The amplitude of component's movements can be inferred from the neutron noise spectra through scale factors (SFs) relating the random displacements to the relative change of the neutron detector signals as previously done in [1,2] for the core barrel (CB). Besides this direct comparison of signals from accelerometers attached to the core barrel and the ex-core detectors has been performed [3].

In order to determine scale factors for measuring the vibration amplitudes of core internals by use of in-core neutron signals, two accelerometers were implemented in different instrument strings and installed inside of two instrument tubes of a 350 MW_{el} PWR. The root mean square of the displacements (RMS_d), of the fuel assemblies (FAs), reactor pressure vessel / core barrel (RPV/CB) and in-core instrument string / instrument tube system (IS/IT, also called lance) were determined from the measured in-core accelerations [4,5]. For the 350 MW_{el} PWR neutron-mechanical scale factors were determined from the normalised auto power spectral densities (NAPSDs) of the in-core self-powered neutron detector (SPND) signals and the auto-powered spectral densities (APSD) of acceleration signals.

In co-operation with the Institute of Nuclear Engineering and Non-destructive Testing (University of Hannover, Germany), Vibro-Meter, Fribourg, Switzerland designed a new version of the existing miniature biaxial accelerometer. This transducer will be inserted inside the Travelling In-core Probe (TIP) tube of a 1300 MW_{el} BWR to characterise and measure the absolute displacements of the tubes.

In-core instrumentation

In Figure 1 the layout of the 350 MW_{el} PWR core and the positions of the in-core instrumentation can be observed. The standard reactor instrumentation consists of five lances (L1,...,L5) each one containing seven SPNDs. In L5 an eighth SPND and the accelerometer A5 were additionally mounted and a sixth extra lance containing two SPNDs of different type (Figure 2) and the accelerometer A6 was installed during one fuel cycle. In the lances the accelerometers and SPNDs are assembled to form instrument strings which are located inside instrument tubes.

The SPNDs have been prompt responding types with Hafnium emitter. They were produced and assembled with the accelerometers into the instrument strings by IKPH.

The accelerometers were tensioned against the inner wall of the instrument tubes by use of the inconel cables passing by from the two SPNDs positioned below the accelerometers. The coupling between the instrument tubes and the accelerometers was tested in a facility outside of the reactor, where the tubes were excited by a shaker and the signals of the in-core accelerometers were compared with those from accelerometers mounted on the outer surface of the tubes. Additionally, the displacements of the tubes were measured by displacement sensors in order to prove the results obtained by integration of the measured in-core acceleration in time and frequency domain.

Figure 1 : In-core Instrumentation in 350 MW PWR

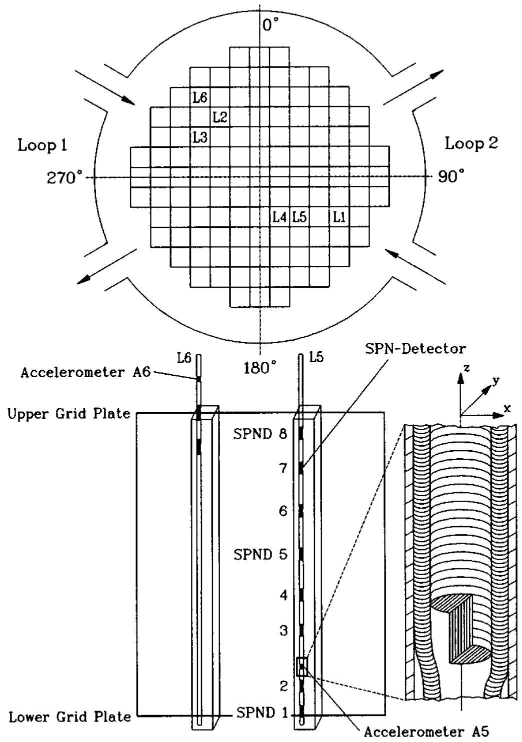


Figure 2. In-core SPN-Detectors and in-core accelerometer CA606, used in PWR

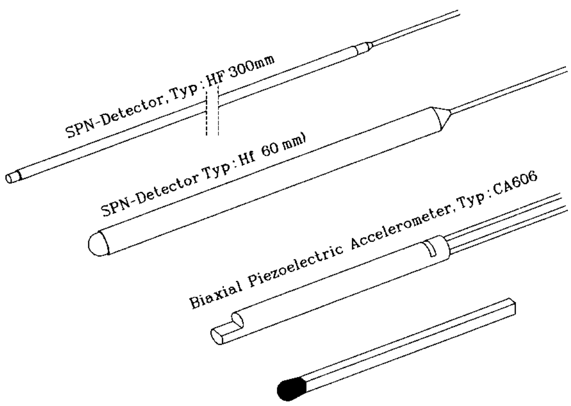
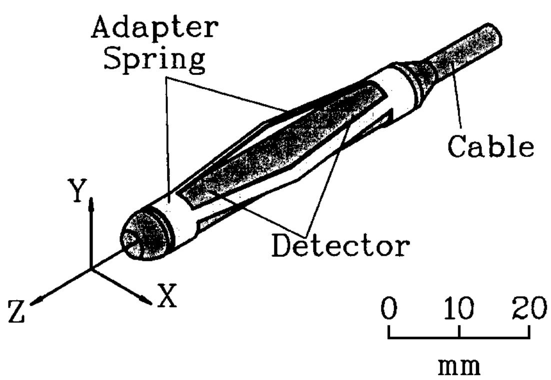


Figure 3. Modified in-core accelerometer CA607 with adapter spring for use in BWR



By means of these pre-operational tests it was confirmed that the coupling between the accelerometers and tubes was sufficient and that the integration of the accelerometer signals leads to the correct displacement values. The accelerometer A5 was placed within the core approximately 70 cm from the lower grid plate and A6 approximately 25 cm above the upper grid plate (Figure 1). The neutron flux at the A5 position was estimated to be 75 times higher than the flux at the A6 position, affecting stronger the lifetime of accelerometer A5.

The piezoelectric accelerometers are a standard product of Vibro-Meter, Fribourg, Switzerland. The miniature biaxial accelerometer CA 606 (Figure 2), having an outer diameter of 4.9 mm is small enough to be assembled in PWR-SPND instrument strings and to be inserted into an in-core instrument tube with an inner diameter of 6 mm.

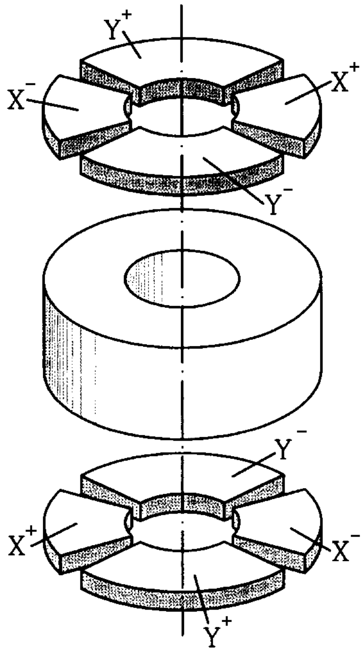
For application in BWRs the design of the accelerometer is effectively imposed by the geometrical envelope that is allowable, i.e. the transducer should fit inside the TIP tube which has an inner diameter between 7 and 8 mm and a total length of up to 42 m with several bends (Figure 8). This means that the transducer shall have two sensitive axes in the X and Y directions and have no sensitivity in the Z axis (same as the accelerometer used in the PWR). This combined with the fact that the lead out cable is also in the Z axis, dictates the long thin pencil-shaped design (see Figures 2 and 3).

The transducer shall be inserted into the TIP tube (Figure 8) by means of pushing the cable. For this reason, an appropriate 4-conductor MI-cable (Mineral Insulated) providing the necessary mechanical strength has been chosen.

The transducer head is pressed against the inner wall of the tube by means of a specially designed spring. The sufficient coupling of the sensor against the wall of the TIP tube has been verified in a test facility, similar to the one which was previously used for PWR application. The whole assembly transducer head / spring does not have sharp edges and is designed for being moved easily forth and back instead of the travelling neutron probe inside the tube.

The sensing elements are using the piezoelectric effect to measure vibrations. The charge output of a piezoelectric ring is proportional to the dynamic compression applied to it. The piezoelectric stack is held together by means of a pre-stressed rod. On top of this rod, there is a seismic mass made of tungsten which is fixed to the piezoelectric stack. It is essential that the pre-stress force does not sensibly change with the temperature, hence a thermal compensation material, a high coefficient of expansion special steel is incorporated in the element in order to match the rates of expansion between the diverse parts within the sensing element and the pre-stressed rod. Under the influence of inertial forces which act perpendicularly to the axis of the pre-stressed rod a seismic mass, bending loads occur, which result in an increase of the compression at one side and a decrease of the compression at the other side of the piezoelectric rings. Each piezoelectric ring has a four-segment electrode mounted on its top face and a four-segment electrode mounted on its bottom face. The opposite pairs of segments are connected together so as to provide a biaxial accelerometer (Figure 4).

Figure 4. Inner construction of the miniature biaxial accelerometer



The integrally attached hard-line cable compromises a MgO insulation and four conductors. These conductors are connected to the electrically separated sensing elements in such a way as to prevent electrical interferences, which would lead to unwanted crosstalk between the two channels. The entire unit (sensing head and MI-cable) is an all welded and hermetically sealed design to a level of better than 10E-09 Torr*lt./sec.

The choice of the piezoelectric material is driven by the operating temperature, the radiation and the design itself which requires very homogenous and stable materials. Vibro-Meter has chosen the natural hydrogen piezoelectric crystal known as Vibro-Meter VC2. This material is not sensitive to hydrogen penetration. Although not required for the specific application, the penetration of hydrogen is drastically reducing the lifetime of common in-core piezoelectrical transducers. Previous applications have shown that the VC2 material survives nearly 10^{21} neutrons per cm^2. In order to obtain the required sensitivity of 2 pC/g output, the number of crystals, together with the total seismic mass can be optimised. Important factors to bear in mind are that the total working mass and length of the two sensing elements in the Z axis should be minimised in order to have the first mechanical resonance of the system well outside the frequency range of interest and so that the system will not be prone to mechanical fatigue under the generally existing vibration levels coming from the vibration of the different components. Therefore the seismic mass working on the crystal stack is composed of a high specific density material (Thungsten) in order to get the maximum mass within the minimum volume.

The biaxial bender design accelerometer is protected by the following patents and their technical data are given in Table 1:

- United States Patent No. 5.117.696,. dated June 2nd, 1992
- European Patent No. 0 316 498, dated March 4th, 1992

Table 1: Technical data of biaxial in-core accelerometers

Type	CA 602	CA 606	CA 607
Dynamic range	0,002 g to 100 g	0,005 g to 50 g	0,005 g to 50 g
Sensitivity	2 x 5 pC/g	2 x 2 pC/g	2 x 2 pC/g
Frequency range (±1-0%)	1 Hz to 700 Hz	1 Hz to 300 Hz	1 Hz to 300 Hz
Temperature range (operating)	-196°C to 600°C	-196°C to 600°C	-196°C to 600°C
Pressure	220 bar / 300°C	220 bar / 300°C	220 bar / 300°C

Quantification of PWR internals displacements

From the acceleration spectra of the in-core accelerometers A5 and A6 , the RMS_d of the vibration of some internals previously identified [6,7] was calculated. The acceleration APSDs of these accelerometers measured during the start up of the reactor after a refuelling at 0% power and the corresponding displacements are shown in Figure 5. The displacements were calculated from the measured acceleration by double integration in time domain as well as in frequency domain. Clearly visible are the peaks due to FAs vibrations (simple / simple supported) approximately at 6 Hz (f_1, first mode) and at approximately 27 Hz (f_2, second mode). The peaks at approximately 8 Hz (f_3) and 14 Hz (f_4) correspond to the RPV/CB movement and the peak at approximately 36 Hz (f_5) is caused by the IS/IT vibration.

The vibration of IS/IT, FAs and RPV/CB are mainly measured in the x-direction by the accelerometer A5 in lance 5. In lance 6 the RPV/CB motion is mainly visible in y-direction, while no vibration of the lance 6 can be observed. Referring to x- and y-directions of the acceleration signals, one has to consider, that x and y for both lances probably are not the same and they don't correspond to the core axis. This is due to the mounting conditions of the lances in the core, where the x- and y-directions of the accelerometers cannot be adjusted.

At 100% power the FA vibration can also be seen by the SPNDs located within the assembly and in the neighbourhood (Figure 6). For example, the SPND-signals of L2 have a coherence higher than 0.4 with signal $A6_y$ of the neighbour accelerometer A6 at approximately 6 Hz and higher than 0.2 at approximately 27 Hz.

From the APSD of the displacement in y-direction the RMS_y-value can be calculated. The procedure of calculation the RMS is based on integrating the shape of a peak given by a linear vibration equation [8]. The resulting RMS_y has the dimension of mm. The RMS-value of the neutron detectors, RMS_n, is calculated from the normalised auto power spectral density in the same frequency range correspondingly. For correlated acceleration and neutron noise signals the neutron-mechanical scale factor SF is then defined by $SF = RMS_n / RMS_y$ [5].

Figure 5. Acceleration and displacement APSDs of A5 and A6 at 0% power

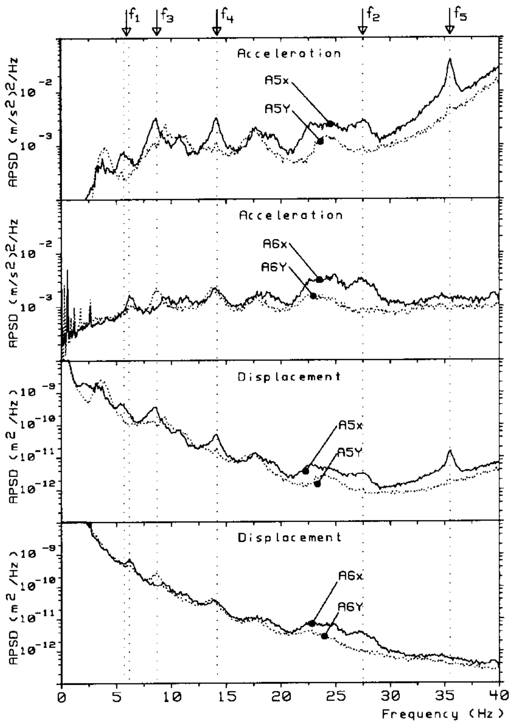
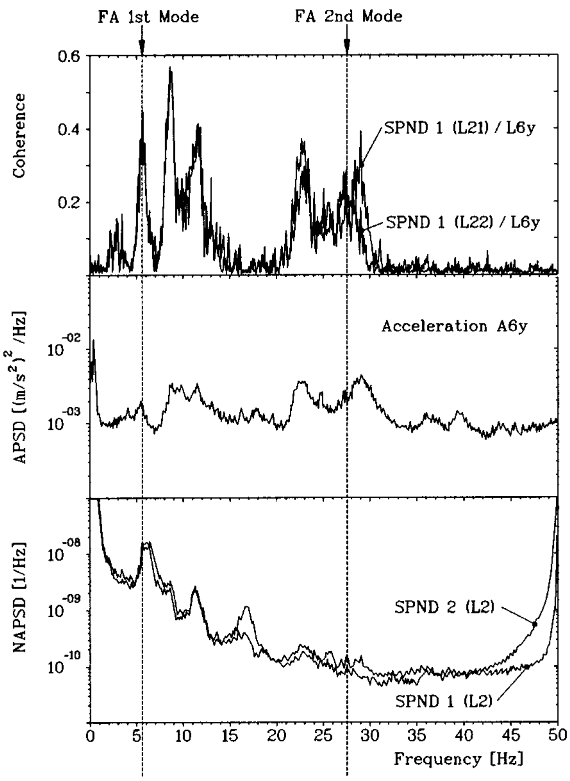


Figure 6. Correlation between in-core acceleration and neutron flux at 100% power



The value of the SFs for the FAs, RPV/CB and the IS/IT for the beginning of the fuel cycle can be seen in Table 2. Using these scale factors, the amplitudes of displacements (RMS_y) caused by the vibration of different components can be determined from the in-core neutron noise spectra.

For the end of the fuel cycle the SF corresponding to the FAs motion was not calculated due to the total loss of sensitivity of accelerometer A5 and the partial loss of sensitivity of A6 in the FAs frequency range motion already mentioned. The RPV/CB SF at the end of the cycle is 5.1×10^{-3}, 24% higher than the SF at the beginning of the cycle.

Table 2: Neutron-mechanical scale factors at the beginning of a fuel cycle of a 350 MW PWR

	RMSn	RMSd (mm)	SF (mm^{-1})
Fuel Assembly	1.5×10^{-4}	0.045	3.3×10^{-3}
Reactor Pressure Vessel / Core Barrel	1.3×10^{-4}	0.032	4.1×10^{-3}
Instrument String - Instrument Tube	8×10^{-6}	0.0028	2.9×10^{-3}

Application to BWR internals vibration measurements

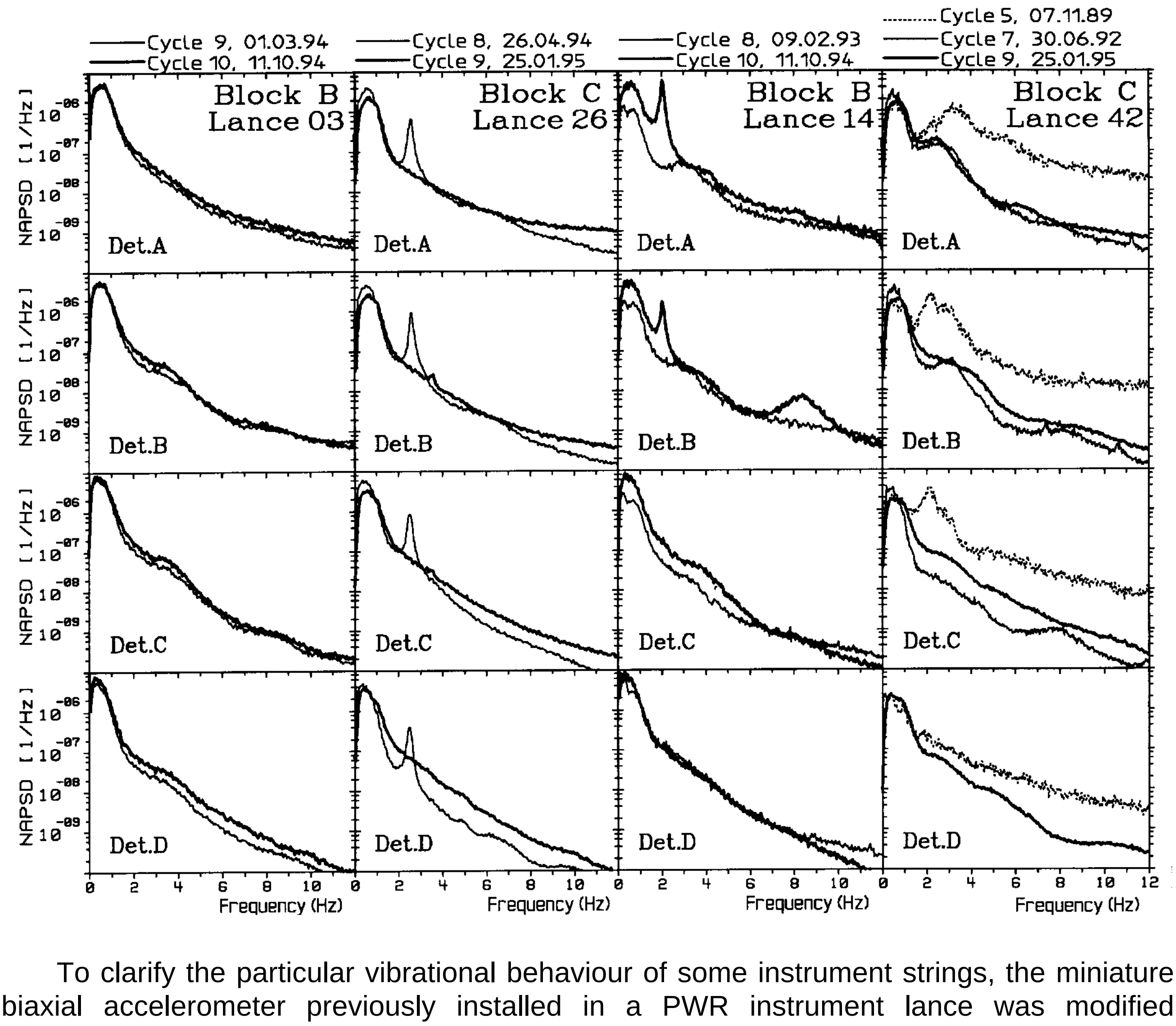
Besides the well-known effects caused by the boiling process and the transport of steam bubbles, the vibration behaviour of BWR internals can be analysed using signals from in-core neutron detectors [9]. The vibrations of the instrument tubes and their possible impact against the surrounding fuel assembly boxes were analysed and analytically modelled [10,11]. The theoretical results of the two models were used to interpret the typical and particular instrument tube vibrations which were measured.

Typical and particular NAPSDs of Local Power Range Monitor (LPRM) signals of different lances of two BWR units observed in different fuel cycles are shown in Figure 7. The shapes of typical NAPSDs are similar to the examples of lance 03 in unit B. In the frequency range from 2 Hz to 4 Hz peaks associated to the vibrations of the ITs can be identified. Deviations from the typical behaviour were found at some core positions. A particular vibration of lance 26 in unit C was detected. The distinct peak around 2.5 Hz was observed in the NAPSDs of all detector signals of lance 26 in the fourth, fifth and sixth fuel cycles [9] with little varying intensities and disappeared during the seventh and ninth fuel cycles, while it appeared in the eigth fuel cycle. At 2.5 Hz the correlations among the signals of different detectors in lance 26 showed high coherences and in-phase behaviour for all combinations except those where the signal of detector B was correlated to the others. It could be concluded that the vibration was strong enough to increase over the transport phenomena and that lance 26 was vibrating in a higher mode between the upper and the lower core grid. A similar particular vibration of the upper part of lance 14 was found in unit B during the tenth fuel cycle (Figure 7). The strong peak at 2.1 Hz in the NAPSDs of detectors A and B was not detected in the previous fuel cycles. It is possible that such particular vibrations of the ITs, which appeared or disappeared after the refuelling but do not change significantly during the cycles, were favoured by specific mounting conditions of the instrument assemblies in those fuel cycles.

At a single core position (lance 42) in unit C another type of particular instrument assembly vibration was found during the fourth, fifth and sixth fuel cycles [9]. The NAPSDs and cross power spectral densities CPSDs of the signals of the upper LPRMs of lance 42 exhibited an significant increased amplitude and damping of the peaks corresponding to the vibration of that IT (Figure 7).

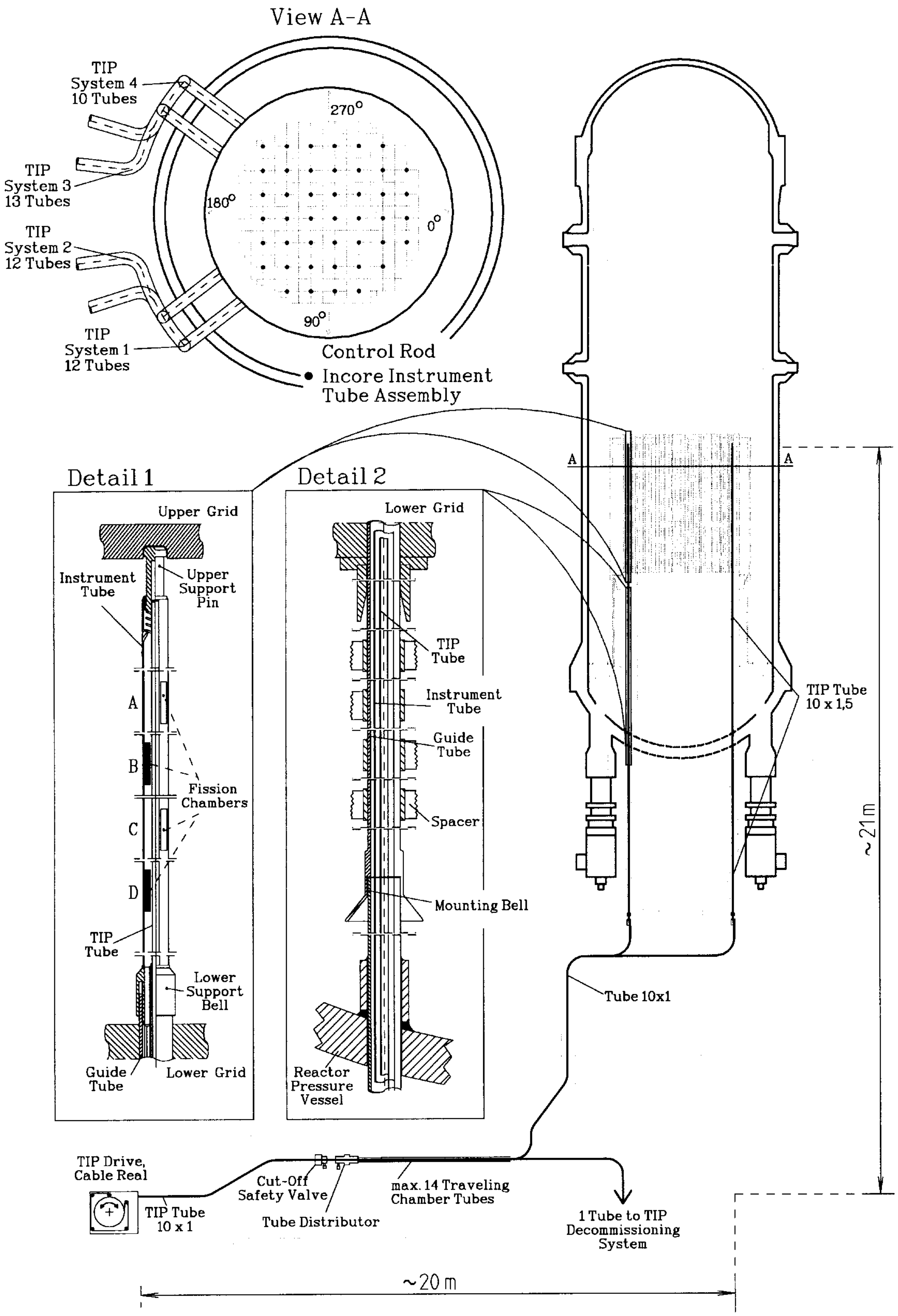
The explanation of this behaviour is impacting of the IT against the surrounding fuel channel boxes or other structures. The theoretical models of vibration and impacting [10,11] showed that in case of impacting the neutron APSD should increase its magnitude specially for the frequencies higher than the first mode vibration and that the peak in the first mode frequency region has a higher damping. At the end of the sixth fuel cycle all the detectors of instrument assembly 42 failed. The instrument tube was replaced and the particular vibration was not observed in the following fuel cycles (Figure 7), but still a deviation from the typical shape could be seen in the NAPSDs of the fission chambers.

Figure 7. In-core neutron noise spectra showing typical and particular instrument tube variations in BWRs



To clarify the particular vibrational behaviour of some instrument strings, the miniature biaxial accelerometer previously installed in a PWR instrument lance was modified to be inserted inside of guide tubes of the BWR-TIP system instead of the neutron probe.

Figure 8. Travelling in-core probe (TIP) system in a 1300 MW_{el} BWR



A full scale model of a TIP system was constructed for testing the adjustable arrangement and coupling of the accelerometer inside of the 42 m long tube. The pre-operational tests have been successfully finished. It could be proved that it is possible to move the accelerometer to any position inside of the TIP-tube from the position of the TIP drive cable real by pushing the cable (Figure 8). The adapter spring (Figure 3) has been optimised and it was shown that the coupling force is high enough to measure the tube vibrations in the frequency range of interest. In the near future an in-core accelerometer will be inserted into the TIP-system of a 1300 MW_{el} BWR. The temporary installation of in-core accelerometers inside of TIP-tube of BWRs is expected to enable a qualitative and quantitative analysis of BWR internal’s vibrations, to determine the neutron-mechanical scale factors and to develop new features of control technologies.

Conclusions

In a PWR two accelerometers were inserted in two different strings and the resulting spectra characterised. Neutron-mechanical scale factors were calculated.

In a full scale BWR Travelling In-core Probe (TIP) facility the feasibility of inserting the accelerometers into the core through a 42 m long tube was successfully tested. In the near future one accelerometer will be inserted into the TIP system of an operating 1300 MW_{el} BWR.

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REFERENCES

[1] Robinson, J.C., F. Shahrokhi and R.C. Kryter (1978). Calculation of the Scale Factor for Inference of PWR Core Barrel Motion from Neutron Noise Spectral Density. *Nuclear Technology*, 40, 35-46.

[2] Robinson, J.C., F. Shahrokhi and R.C. Kryter (1978). Quantification of Core Barrel Motion Using an Analytically Derived Scale Factor and Statistical Reactor Noise Descriptors. *Nuclear Technology*, 40, 47-51.

[3] Thompson, J.P., G.R. McCoy and B.T. Lubin (1980). Experimental Value of Percent Variation in Root-Mean-Square Ex-core Detector Signal to the Core Barrel Amplitude Scale Factor. *Nuclear Technology*, 48, 122-127.

[4] Laggiard, E., J. Fiedler, J. Runkel, H. Starke, D. Stegemann, B. Lukas and D. Sommer (1995). Vibration Measurements in PWR Obrigheim by Use of In-core Accelerometers, *Prog. Nuc. Eng.,* 29.

[5] Laggiard E., Runkel J., Stegemann D., Fiedler J. Determination of Vibration Amplitudes and Neutron-mechanical Scale Factors Using In-core Accelerometers in NPP Obrigheim, Proceedings of Smorn VII, Avignon, France, June 1995.

[6] Runkel, J. and D. Stegemann (1989). Vibration and Noise Analysis at the Primary Loop of Nuclear Power Plants. *VGB Kraftwerkstechnik*, 8, 655.

[7] Fiedler, J., E. Laggiard, J. Runkel, H. Starke and U. Südmersen (1994). Analyse des Schwingverhaltens von Kerneinbauten im DWR des KWO, IKPH Report, 194/94.

[8] Thie, J.A.(1975). Theoretical Considerations and their Application to Experimental Data in the Determination of Reactor Internals' Motion from Stochastic Signals. *Annals of Nuclear Energy*, 2, 253-259.

[9] Runkel J., Laggiard E., Stegemann D., Fiedler J., Heidemann P., Mies H.P., Oed R., Weiß F.-P., Altstadt E. Application of Noise Analysis in Two BWR Units of Nuclear Power Plants Gundremmingen, Proceedings of Smorn VII, Avignon, France, June 1995.

[10] Laggiard E., Runkel J. and Stegemann D. (1993). One-dimensional Bimodal Model of Vibration and Impacting of Instrument Tubes in a BWR, *Nucl. Sci. Eng.*, 115, 62.

[11] Laggiard E., Runkel J. and Stegemann D. (1995). Three-dimensional Model of Vibration and Impacting of Instrument Tubes in a BWR and Transfer from Mechanical to Neutron Noise, *Nucl. Sci. Eng.*, 120, 124.