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Identification of Vibrational Effects in KNK-II Fuel Elements

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Abstract

Several observations indicate vibrational effects in some fuel elements of the KNK-II core. This report describes how the coolant outlet temperature of each fuel element was used successfully as a means of the identification of these vibrations. As a result the cause of the sharp peaks in the power spectral density of the KNK-II reactivity noise was found.

Identifikation von Schwingungen an KNK-II Brennelementen

Zusammenfassung

Aus verschiedenen Beobachtungen an der KNK-II war zu vermuten, daß an einigen Brennelementen Schwingungen auftreten. Hier wird beschrieben wie die Kühlmittelaustrittstemperatur am Brennelementkopf zur Identifikation dieser Schwingungen erfolgreich eingesetzt wurde. Damit ist die Ursache für die scharfen Resonanzen im Reaktivitätsspektrum der KNK-II gefunden.

Contents

1. Introduction

The power spectral density of the neutron flux fluctuations of the KNK-II /1/ shows quite sharp peaks in the frequency range above 1 Hz. In Fig.1 the result of a measurement of the power spectral density at full power is shown. The amplitude of the peak at about 5 Hz corresponds to an almost harmonic oscillation with an amplitude of about .5 ¢. This contribution to the neutron flux fluctuations can also be seen directly in a neutron detector signal itself.

From earlier measurements /2/ it was found that the frequency values at which the peaks appear vary proportionally with the power and the flow rate. (At the KNK-II the power and the flow rate in the primary coolant loop are kept at a fixed ratio). A proportionality between frequency value and flow rate is a characteristic for a flow induced phenomenon /3/. Therefore one has to look for flow induced vibrations of some core internals. The most likely candidates are the control rods and the fuel elements. By means of seismic transducers mounted on the control rod drive mechanism it was proved that the neutron flux resonances cannot be caused by control rod vibration /4/.

But it is well known that fuel elements may perform flow induced vibrations /5,6,7/. Unfortunately there is no real chance of measuring directly the motion of an individual fuel element because mounting any vibration transducers on the fuel elements would be almost impossible during normal power generation or at least very expensive. By the reactivity effect which is very sensitive to fuel motion an individual fuel element cannot be identified especially in the small fast core of the KNK-II the neutronic behaviour of which can be described well by the point reactor model.

However, it will be shown in this paper, that there exists a possibility, which allowed to identify vibrating fuel in some fuel elements in the KNK-II core.

2. The Coolant Outlet Temperature Signal as a Means of Identification

At the KNK-II like in many other reactors there is only one type of signal available which may give information about individual fuel elements: It is the coolant outlet temperature signal measured with thermocouples being installed above each fuel element.

The neutronic behaviour of the KNK-II can be described fairly well by the point reactor model. If therefore a reactivity fluctuation would be caused by only one vibrating fuel element this would induce a corresponding power fluctuation which is common to all fuel elements. Consequently the coolant outlet temperature of all fuel elements would be affected by this locally induced reactivity fluctuation in a similar way as long as the heat and temperature is propagated in all fuel elements by the same physical process (i.e. by heat conduction and coolant flow). Under these circumstances it would be not possible to identify vibrational effects in an individual fuel element by means of the coolant temperature. But the vibration of fuel will cause additional temperature fluctuations. This additional noise depends on the particular vibration mode being attributed to an individual fuel element and will be absent in non vibrating fuel elements.

Any horizontal vibration of a fuel element is expected to influence the turbulent flow pattern which should be seen in the thermocouple signal. The movement of the entire fuel element as well as the movement of the pin bundle with respect to the wrapper tube cause this effect. However, this effect is probably very small.

A rather big noise contribution is expected from the fact that the thermocouple for the coolant outlet temperature is not directly fixed to the fuel element head. As shown in Fig.2 the thermocouples are located 20 mm above the upper orifice for the coolant outlet and within a perforated thimble being welded on a separate instrumentation plate. Let us assume that each fuel element is vibrating in the core region producing its specific contribution to the overall reactivity effect, which is measured in the neutron flux signal. Part of this vibration is transmitted to a correlated movement of the fuel element head. Since the thermocouple is separately fixed there is a relative movement of the thermocouple and the fuel element head which is specific to each fuel element. In spite of the flow mixer a small radial temperature gradient can be expected in the coolant flow at each fuel element outlet. Therefore any horizontal vibration of the whole fuel element must cause a temperature fluctuation at the thermocouple in addition to the normal noise. Simultaneously the flow pattern around the thermocouple thimble fluctuates. Therefore the direct sodium stream to the thermocouple surface through the holes of the thimble may also oscillate and induce a temperature oscillation.

Due to these effects it seems at least theoretically possible to identify vibrational effects in a fuel element by means of coolant outlet temperature fluctuations. Whether the application of this method is successful depends on the fact of whether these temperature fluctuations will be big enough to be detected in the presence of the normal temperature noise.

An estimation of the effect due to the radial temperature gradient will be given now: Let us assume that the fuel element vibrates with an amplitude of 1 mm which corresponds roughly to the clearance between the central fuel element and the adjacent fuel elements in the first ring at the upper load plane during power operation /8/. In addition we assume a temperature difference of a few degree centigrade (e.g. 3 K) across the coolant outlet orifice at the fuel element head (diameter 25 mm). This temperature gradient seems reasonable in spite of the mixer which is located between the fuel pin bundle and the fuel element head. Thus a temperature fluctuation of about 0.1 K is induced. Additionally the measured temperature signal is damped by the low pass characteristic of the thermocouple which has a time constant of about 1 s. This results in a signal damping by a factor of about 30 at the frequency of interest. Thus the amplitude for the vibration induced temperature noise is expected to be in the order of $3 \cdot 10^{-3}$K. Comparing this very small signal with the normal thermocouple noise seemed at first very discouraging. But if the vibration is an almost periodic function, its power spectral density would be a sharp resonance or even a single line and hence by analysis with high frequency resolution this effect should be seen more pronounced than in standard measurements performed routinely.

Whether two signals are correlated or not is usually verified by the measurement of the coherence function between the two signals. In this function all signal contributions which are not common to both signals are eliminated provided that the measuring time is sufficiently long; transfer functions need not be taken into account. Therefore when looking for additional correlation this technique is only applicable if the signals are not already highly correlated without the effect which is investigated. In this case only the transfer function between the two signals may give information about additional correlation. Fortunately in our case the correlation due to thermohydraulics is very small in the frequency range of interest. Therefore both, coherence and transfer function are used for the identification of additional correlation.

3. Measurement of the Coherence Functions between the Coolant Outlet Temperature and the Neutron Flux

The coherence function $\gamma_{\phi T}$ between a neutron flux signal ϕ and an outlet temperature signal T is influenced by the signal-to-noise ratios of both signals. However, the neutron flux signal is known to be fairly well free of noise at all frequencies at which the peaks appear in the power spectral density. This results from a coherence function measured between two equivalent detector signals in order to eliminate the detection noise. Therefore the identification will not be handicapped by the neutron detector signal.

For this vibration analysis only frequencies above 0.5 Hz are of interest. Therefore for the tape records and in the subsequent analysis the frequency components below this value were suppressed by high-pass filtering. The high frequency fluctuations of a neutron flux detector signal and 13 thermocouple signals (all picked up from the standard plant instrumentation) were transmitted and tape recorded in a pulse code mode. NOASYS /9/ was used for the analysis of the recorded signals. The resulting coherence functions for the 13 fuel elements are plotted on Fig.3a and b together with the power spectral density of the neutron flux. From this functions six fuel elements of the test zone (see Fig. 6) could be identified as a cause of the reactivity noise:

The coherence function $\gamma_{\phi T}$ for each of these 6 fuel elements shows one or two sharp peaks. Each peak appears at another frequency but all at frequencies where the power spectral density of the neutron flux has also a peak. Very important in this connection is the fact that the frequencies of all these peaks differ from each other and that each one or each pair is characteristic for one fuel element. This proves that the peaks in the coherence function are really caused by power and temperature fluctuations which are specific for the identified fuel elements. Since only the fuel element itself can produce these correlated fluctuations the identification of vibrational effects in individual fuel elements was successfull.

Some of these fuel elements even cause two peaks in the coherence function the second being a higher harmonic of the first one Moreover, the power spectral density of the neutron flux shows a lot of higher harmonics (not presented here) which form groups belonging to each fuel element.

No vibration was detected for fuel element 202 and - as expected - for all the fuel elements of the second (3..) ring*). The second fact was expected due to the bowing effect which bends all fuel elements except the central element towards the steel reflector. As a consequence a gap of about one millimeter appears between the central element and the adjacent elements of the first ring. The gaps between all other fuel elements are considerably smaller if there are any at all /8/ which makes is rather unlikely for them to vibrate at power operation.

4. Influence of Fuel Vibration on the Transfer Function Between the Neutron Flux and the Coolant Outlet Temperature

Though the identification of vibrational effects in fuel elements was already successful by means of the coherence function an additional confirmation has been attempted by means of the transfer function between the neutron flux and the coolant outlet temperature. For our case we can depict the scheme of Fig. 4. The vibration s which is associated with each fuel element and which cannot be detected directly produces in the corresponding coolant outlet temperature T a local component T_{local} through the effects discussed in para.2 (transfer function W). In addition the vibration induces a reactivity effect ρ_s through the transfer function M. For a rather small fast reactor as KNK-II this reactivity and the corresponding neutron flux variation can be described by the point reactor model i.e. this variation is a global effect. With ρ_x all

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* For the time being the third (4..) ring was not examined.

other reactivity variations are summarized including those from vibrations of other fuel elements. The global power or neutron flux variation ϕ induces in each fuel element a component T_{power} of the coolant outlet temperature (via transfer function V). The sum of both components (T_{local} and T_{power}) and the additional temperature noise T_{noise} (normally also a local but uncorrelated effect) is the measured coolant outlet temperature T.
According to this model one obtains

$$\frac{CPSD(\phi,T)}{APSD(\phi)} = V + \underbrace{\frac{G^{*}\cdot M^{*}\cdot APSD(s)}{APSD(\phi)}}_{= 0 \text{ for a fuel element at rest}} \cdot W$$

The ratio of the cross and auto power spectral densities on the left hand side can be determined from the only measurable quantities ϕ and T. The neutron flux ϕ is representative for all fuel elements and the outlet temperature signal T belongs to an individual fuel element. The transfer function V which is measured for a non vibrating fuel element can also be calculated. This function is given by the heat transfer in the fuel element. Therefore it is similar to all fuel elements and is a smooth curve in dependence of the frequency.

If however the measured ratio shows sharp peaks being characteristic for individual fuel elements it will be an additional proof of vibrational effects in these fuel elements. This follows from the above given equation: For a fuel element with vibration the measured ratio is changed with respect to V by the second term on the right hand side. Obviously the magnitude of this term equals that of the transfer function W as long as there is no other contribution to the neutron flux at the particular frequency.

The measurements show exactly this behaviour as demonstrated in Fig.5 for three representative fuel elements. A fuel element at rest shows the normal transfer function V, the smooth shape of which corresponding to the theoretical prediction. However, a fuel element subjected to some kind of vibration produces an additional sharp peak in the measured transfer function between power and its coolant outlet temperature signal. This peak specific to each fuel element is an indication for the fuel vibration in the corresponding fuel element.

An additional useful information with regard to any possible consequences would be the vibration amplitude s. Due to the various effects which are possibly involved in the transfer function W (see para.2) it seems for the moment impossible to obtain this information from the temperature T (see Fig.4). But it should be possible to estimate s from the measured power fluctuation. Since the peaks of the APSD(ϕ) exceed considerably the neighbouring level, the component in the APSD(ϕ) due the vibration can be fairly well separated just by subtraction of the interpolated background level. With this result ρ_s can be calculated as G is known. The transfer function M can be obtained e.g. by means of neutronic perturbation calculations. From both quantities ρ_s and M the vibration amplitude s can be estimated (see Fig.4). A preliminary result from a two-dimensional perturbation calculation shows that the vibration amplitudes in the core region are in the order of about 1/2 mm.

5. Conclusions

The sharp resonances in the reactivity power spectral density measured at KNK-II are caused by vibrational effects in fuel elements. The identification of these fuel elements subjected to vibration and their contribution to the total reactivity spectrum was found experimentally by the measurement of the coherences between the neutron flux and the coolant outlet temperatures of different fuel elements. It seems that the special design of the fuel element head and thermocouple mounting at KNK-II promoted the successful identification.

The main use of the thermocouple signals is the identification, whereas the reactivity signal may be used to determine the fuel motion in more detail. Especially from the large number of higher harmonics it is expected to find the vibration modes. For this purpose the phase lags between the fundamental mode and the higher harmonics must be determined, which can be done using a technique described in /10/.

Due to the proportionality between the frequencies of the resonances and the coolant flow rate the vibration is expected to be caused by a flow induced effect. Changes of a fuel element's coolant flow rate and/or its mechanical characteristics (e.g. by fuel pin swelling) should effect the frequency behaviour. Therefore monitoring the vibration during the fuel elements' lifetime should be useful.

Even if the vibrational effects or its changes are not understood quantitatively any suspicious changes or those which are not common to all fuel elements should be a reason to pay special attention to the corresponding fuel element.

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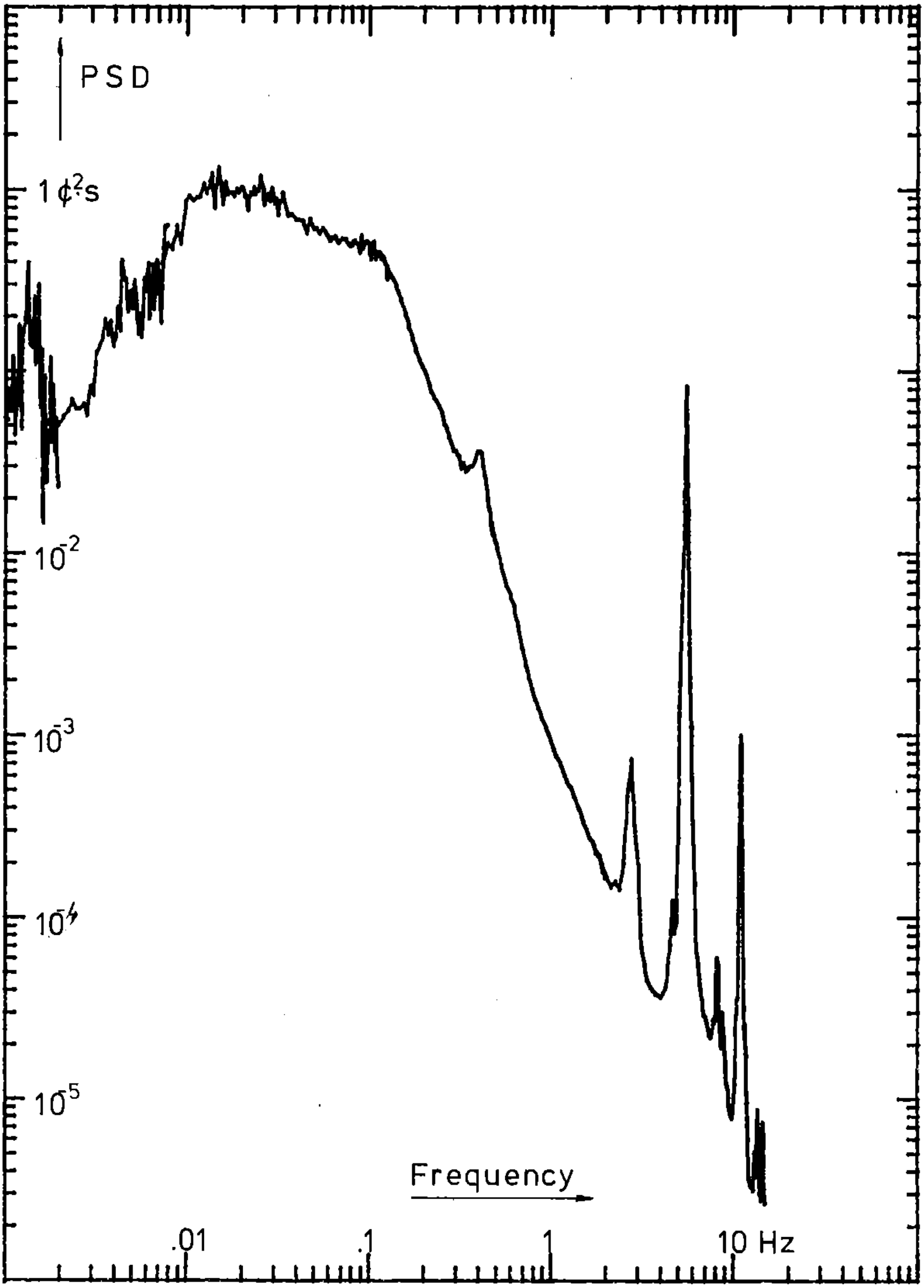

Fig.1 Power spectral density of the reactivity noise of the KNK-II at 95% of full power.

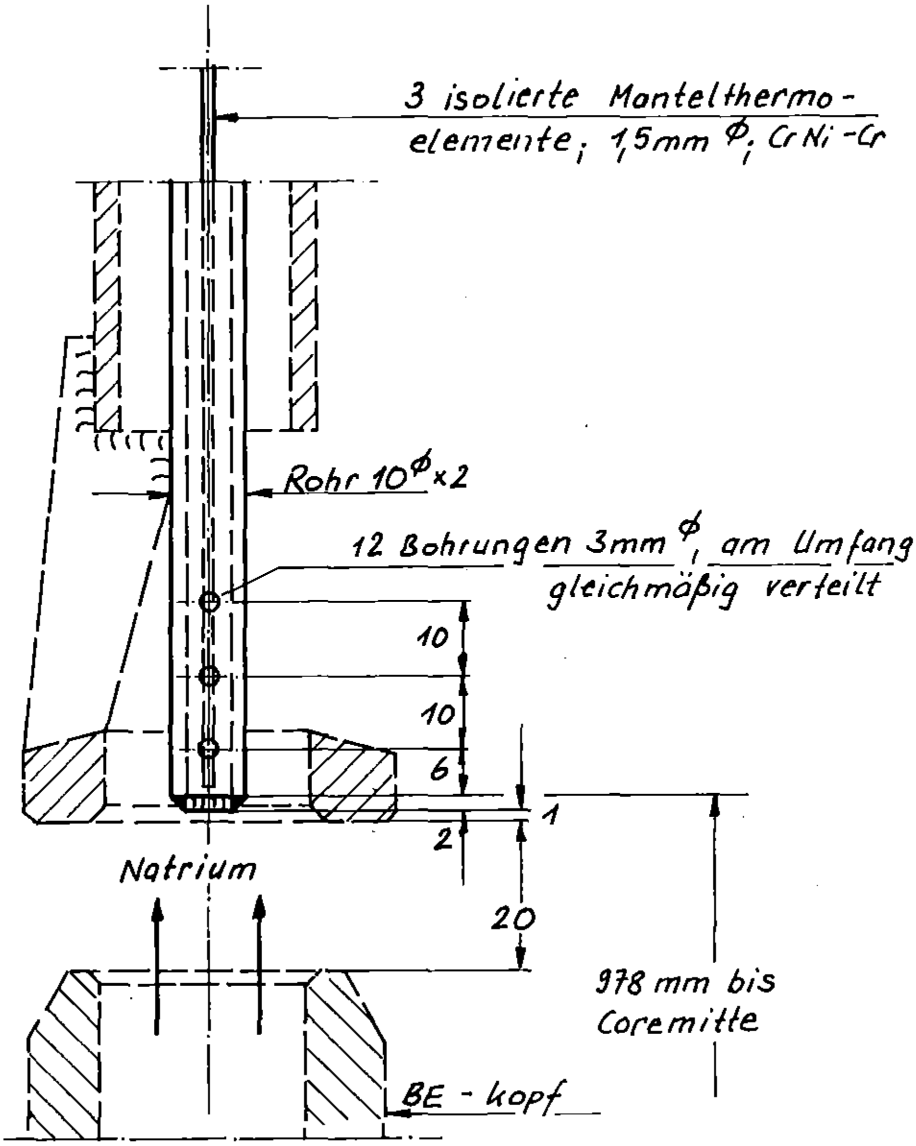

Fig.2 Location of the thermocouple of the plant instrumentation above a fuel element for measuring the coolant outlet temperature.

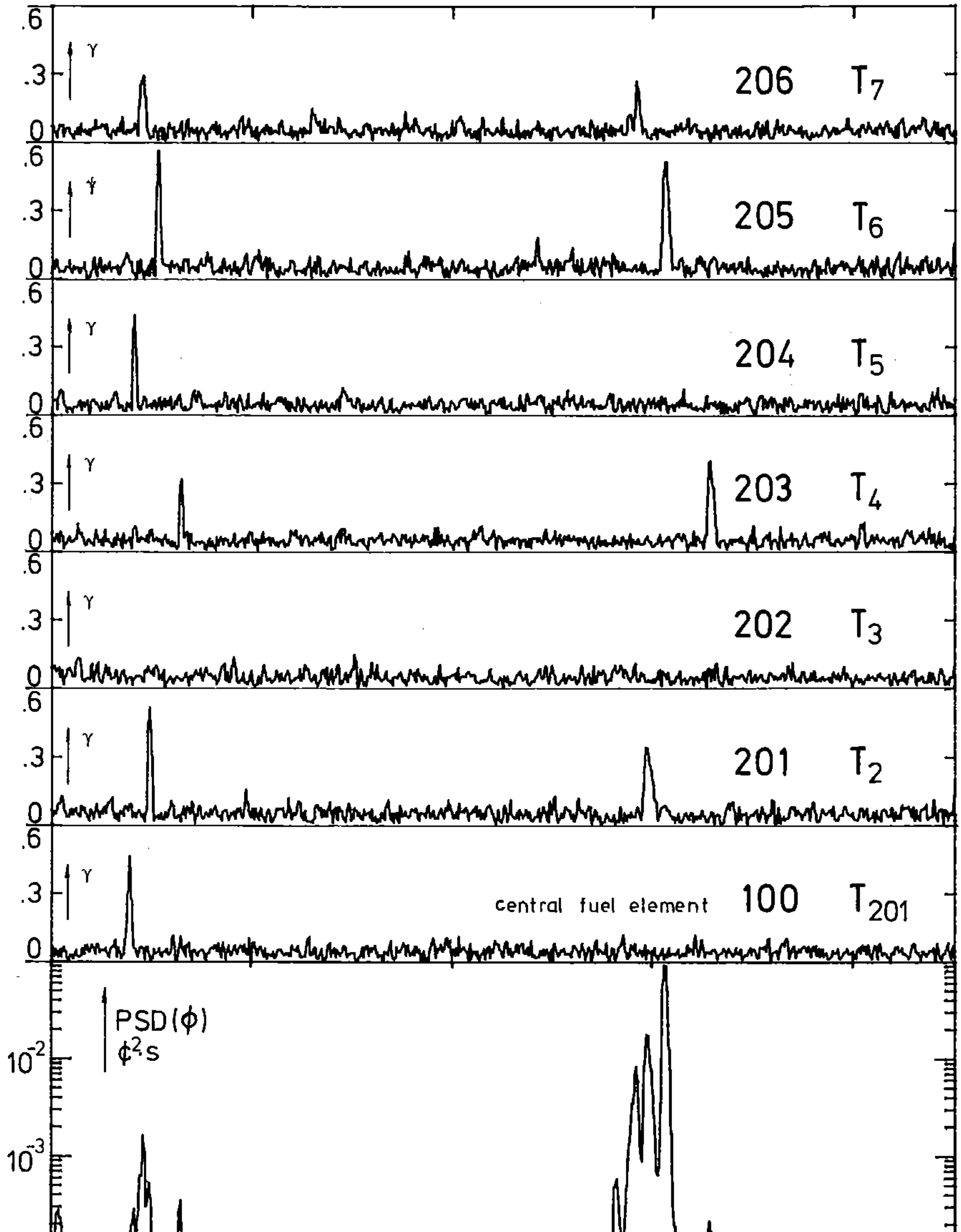

Fig. 3a Power spectral density of the neutron flux and coherence functions between the signals of the coolant outlet temperatures of all test zone elements and of the neutron flux.

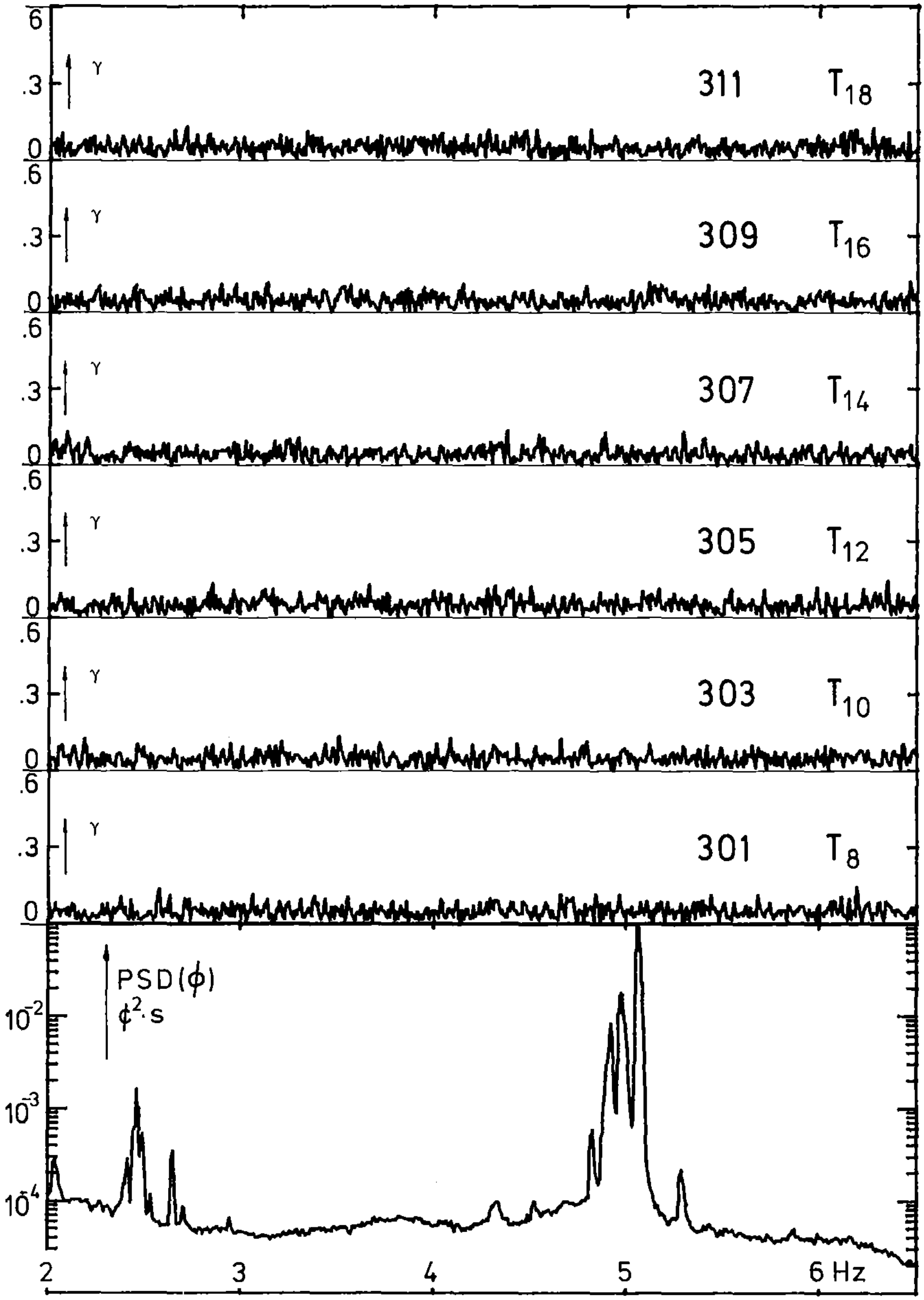

Fig.3b Power spectral density of the neutron flux and coherence functions between the signals of coolant outlet temperatures of driver zone elements (second ring) and of the neutron flux.

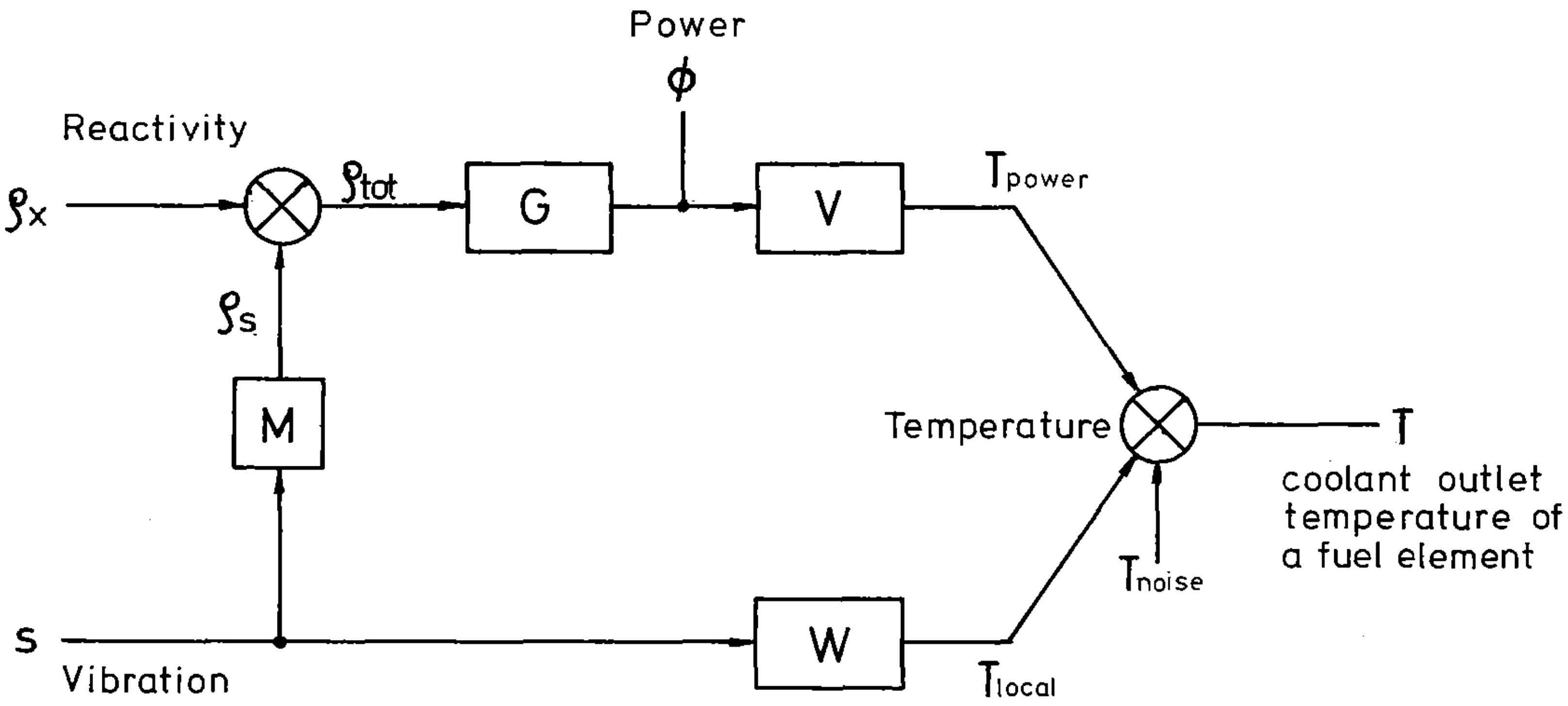

Fig.4 Schematic diagram for vibration in a fuel element.

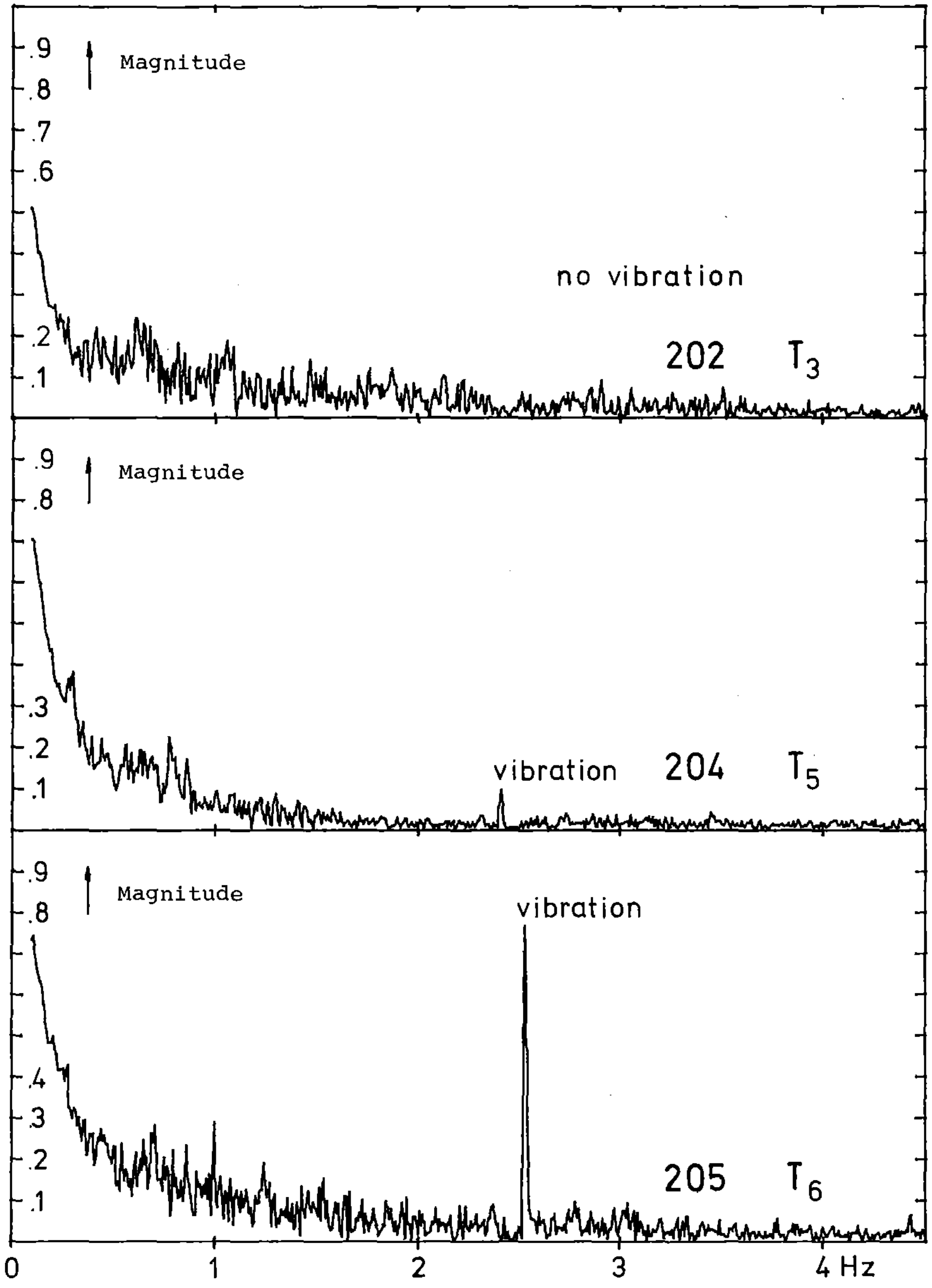

Fig.5 Measured transfer functions between the power and the coolant outlet temperatures of three fuel elements. (Normalized to the power and to the temperature rise).

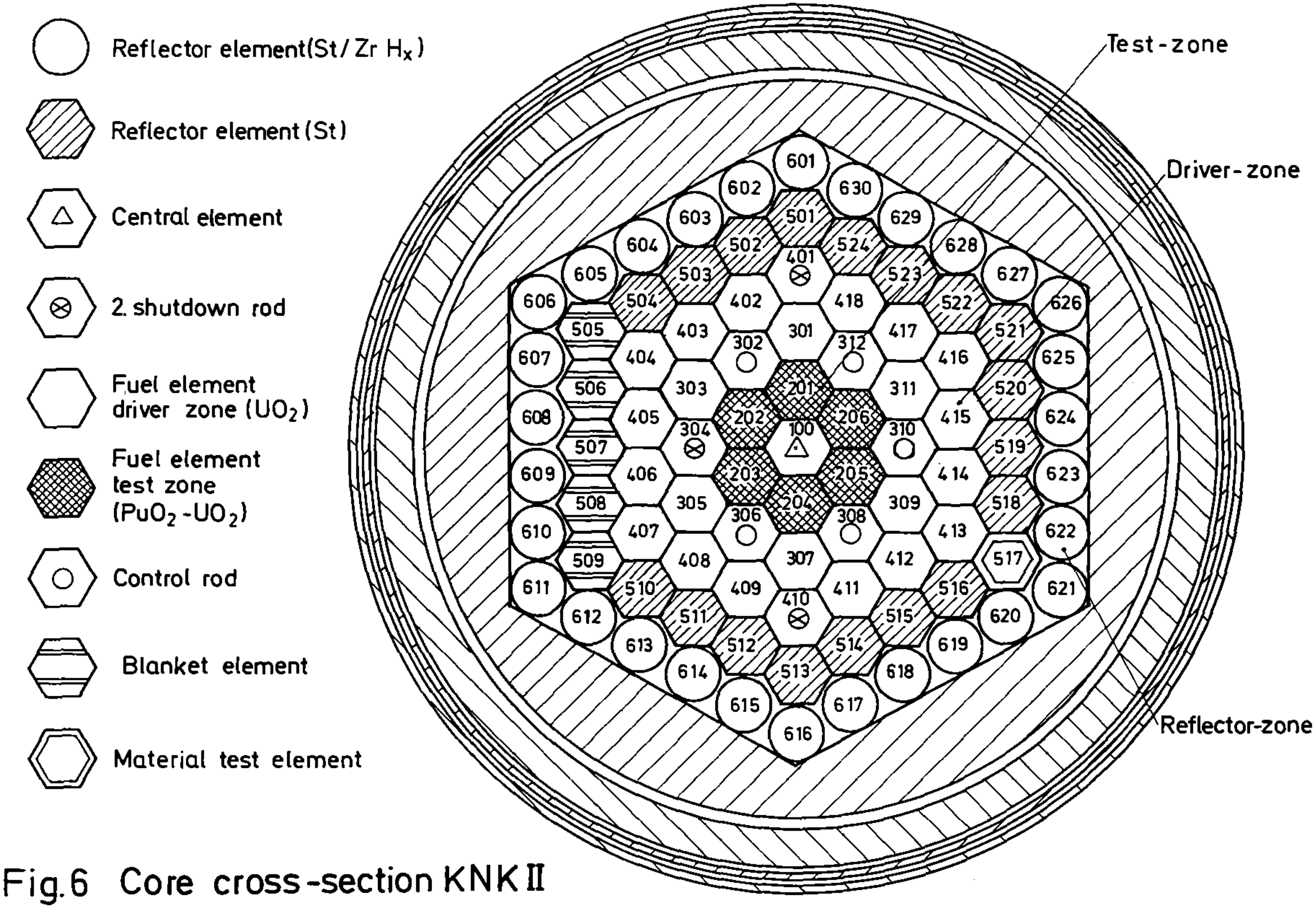

Fig.6 Core cross-section KNK II