Monitoring of Flow-Induced Fuel Element Vibration at KNK II

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SUMMARY

The reactivity of the KNK II /1/, a sodium cooled fast test reactor, showed almost harmonic oscillations with amplitudes of $\Delta\rho \leq .25$ ¢ and definite frequencies. As the oscillation frequencies varied proportionally with the flow rate it was concluded that flow-induced vibration of some core internals might be the cause.

The control rods could be eliminated as possible candidates by measurements with seismic transducers mounted on the control rod drive mechanisms. Due to the lack of an in-core vibration instrumentation any fuel element vibration could not be checked directly. However, by sensitive correlation measurements between the reactivity and the fuel element coolant outlet temperatures it could be shown that the fuel elements of the reactor testing zone caused the reactivity oscillations.

The fact that the vibration was present only at power operation is explained by the bowing effect. By this effect the fuel elements are tightened at their pads. It also generates gaps at the upper pad levels between the central fuel element and its neighbours. Thus only the 7 central fuel elements became susceptible to elastic vibration.

Measurements under various operational conditions and theoretical considerations showed that the flow-induced vibration must have been caused by vortex shedding or jet switching. According to the measured frequencies and the Strouhal numbers, vortex shedding at each fuel element outlet nozzle seems to be most likely. The induced mechanical strains have been estimated and turned out to be of no concern. There are indications for a relationship between the detected vibration and independently observed wear marks on the fuel pins /2/. A clear statement on this is expected from further post irradiation examinations.

1. Introduction

Sensitive reactivity monitoring at KNK II, a sodium cooled fast test reactor with 58 MW_{th} /1/, showed almost harmonic reactivity oscillations with amplitudes up to 0.25 ¢. They show up in the corresponding power spectral density function (PSD) as sharp peaks (Figs. 1 and 2). Because of the particular frequency characteristic it could be concluded that they were caused by flow-induced vibration of some core internals. Measurements with seismic transducers fixed on the casings of the control rod drive mechanisms showed however, that the conspicuous reactivity oscillations were not caused by control rod vibration. Direct detection of fuel element vibration would have required an in-core instrumentation which was not available at this reactor. However by means of the thermocouples for coolant outlet temperature monitoring of individual fuel elements it could be demonstrated that vibrating fuel elements of the test zone caused the reactivity oscillations. As fuel element vibration with similar characteristics has obviously not been observed before, efforts have been made in order to classify the flow-induced vibration and to identify the particular excitation mechanism. This is necessary for estimating vibration induced strains and for assessing whether other mechanical effects might be related.

2. Identification of the reactivity oscillations

As KNK II behaves according to the point reactor kinetics model, a localization of reactivity effects is impossible by means of the reactivity signal only. But sensitive cross-correlation measurements between the reactivity signal ρ, derived from out-of-core BF_3-ionization chambers, and fuel element coolant outlet temperature signals T showed the following result (Fig. 2): The coolant outlet temperature T_i of a particular fuel element "i" is correlated with the reactivity at one (or more) well defined frequency (frequencies) with small bandwidth ($\Delta f/f \lesssim .01$) at which the power spectral density of the reactivity PSD(ρ) has peaks. This cannot be caused by the observed integral power oscillations and by corresponding coolant temperature oscillations because this would affect all fuel elements in a similar way. In addition this temperature oscillation would be too small for detection. The same holds for local power variations induced by vibration.

But horizontal vibration of a particular fuel element outlet nozzle relative to the thermocouple, which is fixed 2 cm above this nozzle at a separate instrumentation plate, can induce oscillations of the corresponding coolant outlet temperature. It was estimated e. g. that a radial temperature difference of about 3 K across the outlet nozzle, which seems reasonable in spite of the flow-mixer, would be sufficient to explain the measured coherence function γ /3/. Therefore the correlation between T_i and ρ observed at a particular frequency f_i was used to identify the fuel element denoted by "i" as the cause of this reactivity oscillation. However, all further information about the fuel element motion was derived from the reactivity signal alone.

As an example Fig. 2 shows the reactivity spectrum (PSD(ρ)) together with the coherence functions $\gamma(\rho,T_i)$ between ρ and the signals T_i for all seven fuel elements of the testing zone (see also Fig. 3). The coherence functions $\gamma(\rho,T_i)$ show one or more sharp peaks for five of them, clearly indicating a correlation between ρ and T_i. Often correlations for all fuel elements of the testing zone were fond. The frequencies of all peaks of the coherence functions $\gamma(\rho . T_i)$ differ from each other and they appear at frequencies f_i where the reactivity spectrum has also peaks. The fact that each peak (or pair of peaks) is characteristic for only one individual fuel element proves that they are really caused by temperature fluctuations of individual fuel elements.

In this way it could be shown that only fuel elements of the testing zone showed this type of vibrational effects.

3. Investigation of the vibrational behaviour

So far the correlation measurements allowed the localization of the reactivity effect only. Further analysis at different power levels showed that the oscillation frequencies, f_i, of all fuel elements involved are directly proportional to the power between 30 % and 90 % power levels. As in this operational range the ratio between the reactor power and the total coolant flow rate is kept constant the frequencies f_i are also proportional to the coolant flow rate. Theoretical considerations concerning the parameters which influence the frequency and auxiliary measurements at which the ratio between the power and the flow rate was changed show that the frequencies are shifted by the coolant flow proportionally to it. This indicates a flow-induced phenomenon and more specificly a fluid dynamic effect as excitation mechanism.

A comparison (Fig. 1) between the PSD(ρ) measured at full power and zero power but at a similar flow rate shows that all peaks related to the fuel elements are completely absent at zero power. On the other hand the broad band reactivity noise above .5 Hz is considerably bigger at zero power than at some power. In order to understand this result additional measurements were performed between zero and 30 % power levels, a range in which the coolant flow is kept constant (corresponding to 30 % power) to build up the coolant temperature rise. They showed that the peaks in the PSD(ρ) appear with their characteristic pattern between 10 and 15 % power level (see Fig. 4). (In the same power range the static power coefficient changes considerably.)

These results can be explained in the following way: At zero power the fuel elements are standing relatively loosely in their carrier units and are subjected to flow driven random movements within the clearances at the pads (.6 mm at the upper and .1 mm at the lower pads). This causes the big reactivity noise level above .5 Hz in a wide frequency band. With power ascension the clearances are used up due to the bowing effect and contact forces build up at the pads. Thus random movements of the whole fuel elements are no longer possible. Hence the general reactivity noise level above .5 Hz is decreased. (The increasing noise level below .5 Hz is due to temperature effects related to the heat removal.) On the other hand when the fuel elements are tightened at the pads through the bowing effect they become also susceptible to elastic vibration. As all fuel elements are bent outward in their upper parts, except the central fuel element which is not exposed to a horizontal temperature gradient, a gap of about 1 mm develops between the central fuel element and each of its neighbours, /4/, (see Fig. 5). Consequently only for the fuel elements of the testing zone a clearance at the upper pad level is left which allows a horizontal vibration with the lower end fixed and the upper end free. This fact can explain why oscillations could be ovserved only for the fuel elements of the testing zone and only at reactor power levels (above 10 % of full power) where the bowing effect is strong enough to fix them at their lower parts. The clamping also explains qualitatively the observed deviation from the proportionality between f_i and the flow rate in the power ranges below 30 % and above 90 %. In these ranges the coolant temperature rise changes. Hence the radial temperature gradient is changed and consequently also the core clamping by means of the bowing effect. This was confirmed by additional measurements for which the average coolant temperature and the coolant temperature rise were varied separately at a constant coolant flow. The frequencies increase with increasing temperature rise.

It has also been considered whether non-mechanical effects such as gas bubbles in the coolant, flow fluctuations or even sodium boiling could cause the reactivity oscillations. But according to the experimental results and to reactivity calculations these possibilities must be excluded.

From the measured reactivity amplitude a displacement of about .2 mm at the upper pad level was calculated. This must be attributed to a motion of whole fuel elements in the testing zone within the gaps at the upper pads. Vibration of the pin bundle within the wrapper tube can be excluded because of the axial disalignment of the bundle which makes the clearances provided between the spacer grids and the wrapper tube ineffective. In addition the observed differences between power and zero power operation could not be explained in this case. The latter argument holds also for coherent fuel pin vibration within the spacer grids. From all these considerations it must be concluded that whole fuel elements vibrate in the radial core direction.

As excitation mechanism a fluid dynamic effect must be assumed according to the proportionality between f_i and the flow rate. For the same reason the usual excitation by turbulent flow fluctuations must be ruled out because in this case essentially only natural modes of the structure would appear /5/. An oscillation like a fluid conveying pipe must also be excluded, because the corresponding oscillation frequencies do not increase proportionally with the flow rate /6/. Far field excitation by a source outside the core is also impossible because it should impose the same frequencies on all fuel elements involved.

The following additional observations will give some information about the fluid dynamic effect: The Figs. 1 and 2 indicate the existance of higher harmonics. A special analysis /7/ showed that higher harmonics of each fuel element appeared indeed. From measurements with high resolution an extremely small half band width of $\Delta f/f \approx 3 \cdot 10^{-3}$ was determined for the oscillation. This is in agreement with a very long coherence time bigger than 200 s which could be measured for one vibrating fuel element. These are strong indications for a self-sustained oscillation. Its characteristic feature is a strong periodicity, the frequency of which is controlled by the vibrating system itself, in this case by the coolant flow. Especially the proportionality between the frequency and the coolant flow is typical for vortex shedding /6/. For fixed structures its frequency f_s is given by /6/

$$f_s = S \frac{v}{D} \tag{1}$$

where S is the Strouhal number, v is the free stream velocity and D is a characteristic length of the vortex shedding structure. According to this relationship the coolant inlet throttle may be a possible location. For the coolant outlet nozzle and the hydraulic hold down unit the Eq. (1) could not be applied as the pertinent parameters are not known. As the application of Eq. (1) is limited to fixed structures which may not always be correct in our case it is used as an approximate guideline only.

4. Interpretation by a nonlinear fluid oscillator model

The existance of higher harmonics with amplitudes being some times even bigger than those of the fundamental modes cannot be explained by neutronic effects or by spatial modes of the structure /8/. However higher harmonics may well be caused by nonlinear fluid mechanical effects such as vortex shedding. For its description generally an oscillator model is applied consisting of two coupled differential equations, one for the structure and another one for the fluid /9/.

For the former normally the linear equation for a spring mass system excited by the fluid oscillation is used and for the latter the nonlinear inhomogeneous Van der Pol Equation is applied /9/. An analysis of this system gives the following results /8/. The common oscillation frequency f_o of this coupled system is approximately equal to the vortex shedding frequency f_s. This is in good agreement with the measurements and explains well the observed frequency dependence upon the flow. But f_i depends also on other parameters of the fluid and the structure. This fact can explain the deviation from the proportionality between f_i and the flow rate in the low and high power ranges where the core clamping forces change. For the same reason a spatial separation between the wake from where the vortices are shed and the vortex-induced vibrating structure seems also unlikely because in this case a feedback from the vibrating structure to the wake would hardly be possible.

In addition the nonlinearity of the Van der Pol Equation leads to oscillations with subharmonic and superharmonic frequencies /10/ with even and odd integer ratios being in good agreement with the experimental results. The theory allows also for the possibility that the higher harmonics may have bigger amplitudes than the fundamental mode, which was also observed.

Obviously this model can explain at least qualitatively all characteristics of the observed oscillations which are rather uncommon for fuel element vibration but which are well known from other technical systems e. g. cross-flow in tube bundles of heat exchangers.

It must however be realized that the Van der Pol Equation has been applied also successfully to a whole category of hydrodynamic processes such as the pneumatic hammer, the beating of the heart, etc. /9/. Vortex-induced vibration belongs, among others, to this category. Hence other nonlinear mechanisms of flow-induced vibration must also be considered in our case. Such a possibility could be the flow-induced vibration by jet switching /6/. It may occur if the wake is too small for vortex shedding. Jet switching is expected if $v/(f \cdot D) \geq 75$. Therefore the grid spacers and the fuel element coolant outlet nozzles have to be considered as possible locations.

Due to the fact that whole fuel elements vibrate it seems to be most likely that the excitation either by vortex shedding or jet switching occurs at the flow discharge from the fuel assemblies /11/. In this case relatively small forces would be necessary because of the long lever arm.

So far we have not accounted for the fact that the fuel elements in the ring of the testing zone can move only to the core center (see Fig. 5). With this restriction a harmonic excitation force leads to oscillations with higher harmonics of integer order. This may be an additional cause for the observed higher harmonics. From a special correlation method for higher harmonics /7/ the phase relation between the fundamental and the first harmonic mode was obtained from the measured signals. It indicates indeed such a type of motion.

5. Conclusions

The reactivity is only an indirect signal for the observation of fuel element vibration. However, by using sensitive signal analysis techniques and vibration models, it was possible to identify, to localize and to analyze fuel element vibration. This was achieved by using the normal plant instrumentation at regular plant operation. Therefore this approach fits best the requirements of a monitoring system not disturbing the normal plant operation.

The core tightening by the bowing effect is a necessary requirement for the occurence of the fuel element vibration. Possibly this might be a reason for the fact that this type of vibration has to our knowledge not been observed during previous out-of-pile tests. There is only one case where for fuel elements a proportionality between the frequency (of a pressure oscillation) and the flow rate was observed /12/.

The detected reactivity oscillations are caused by vibrations of whole fuel elements of the testing zone. The vibration induces at the upper pads displacements of ≤ .2 mm. Based on this value strains of ≤ 25 μm/m and ≤ 2 μm/m have been estimated for the wrapper tubes and the fuel pins respectively. This is well within the design specifications.

The vibration is caused by a fluid dynamic excitation such as vortex shedding or jet switching. The most likely location for it seems to be the coolant outlet nozzles.

Finally the question was investigated whether there exists any relationship between this type of vibration and wear marks on pins of two fuel elements for which a post irradiation examination has already been performed /2/. They had performed up to some 10^7 oscillations. These wear marks were found on the cladding of many fuel pins where they contact the grid spacers. In the case they are caused by the observed vibration, they should become bigger with increasing core height according to the increasing oscillation amplitude. This was confirmed by the post irradiation examination. One would also expect that the wear marks would show a pattern typical for the oscillation direction. Only for one from six wear mark patterns which could be investigated for this purpose it was possible to recognize definitely the orientation and this orientation agrees with the direction anticipated for the fuel element vibration.

Therefore it seems possible that the detected fuel element vibration may cause the observed wear marks. However, this question can be definitely clarified only after post irradiation examination of all fuel elements which will be performed anyway.

Acknowledgement

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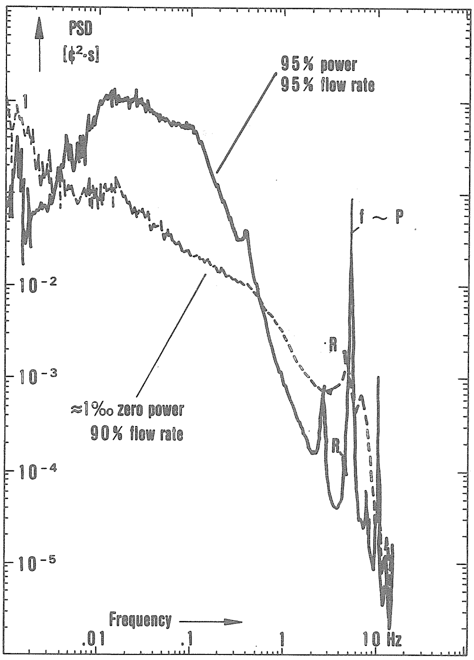

Fig.1 Reactivity Noise at Different Power Levels but Similar Flow Rates in the Primary Coolant Loop

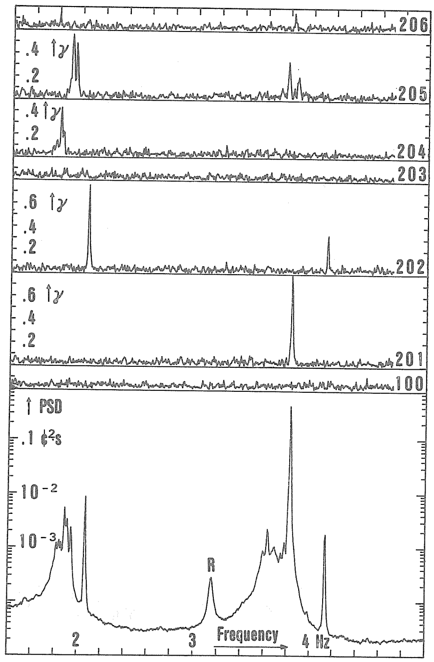

Fig.2 Reactivity Noise and Temperature Correlations i.e. Coherence Functions between the Reactivity and the Coolant Outlet Temperature of the Fuel Elements in the Testing Zone (Measured at 70% of Full Power)

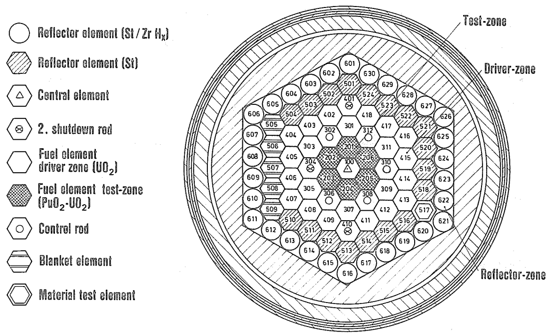

Fig.3 Core Cross-section of KNK II

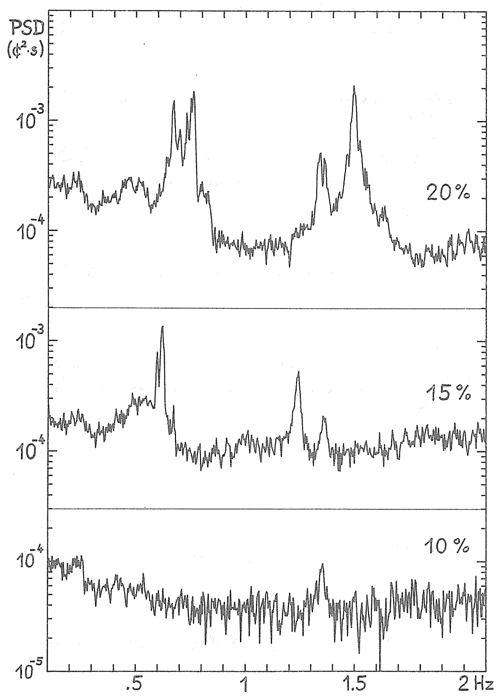

Fig.4 Reactivity Noise at Different Power Levels but at the same Flow Rate in the Primary Coolant Loop (corresponding to 30% Power)

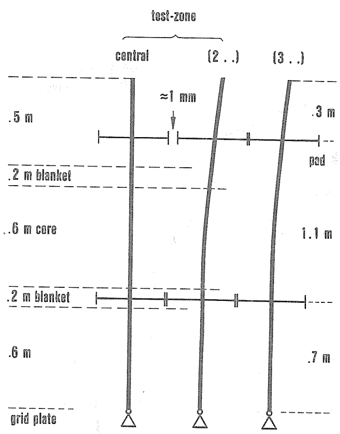

Fig.5 Scheme of Bowed Fuel Elements