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POWER OSCILLATION AND STABILITY IN WATER COOLED REACTORS

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Abstract

Periodic oscillation in measured temperature fluctuation was observed near to surface of a heated rod in certain heat transfer range. The frequency of the peak found in power spectral density of temperature fluctuation and period estimated from the cross correlation function for two axially placed thermocouples change linearly with linear energy (or surface heat) production. It was concluded that a resonance of such surface (inlet) temperature oscillation with the pole of the reactor transfer function can be responsible for power oscillation in BWR and PWR, thus instability is not solely due to reactor transfer function.

1. INTRODUCTION

It is well known that power oscillation can occur in boiling water reactors (BWR) during initial start up at certain power level and flow regime. Such observation is as old as the history of this type: first it was presented in Geneve conference in 1958 [1,2]. From the very beginning this power oscillation was explained by feedback effects in boiling water reactors. It has been shown that due to feedback effects the reactor transfer function of these reactor may have poles, which leads to instability, thus power tends to oscillate. Damping factor was also characterized by this model. This model served always as a basis for stability estimation. Decay ratio (DR) estimated using this model has been generally accepted and today is widely used in BWR operation.

Gialdi et al.[3] presented operational experience of power oscillation in BWR, measuring neutron oscillation by incore neutron detectors. It was shown, that the magnitude of those oscillations is different for different fuel assemblies (coolant channels) and even their phase can be different. The exact nature of those oscillation needed some explanation different from point kinetic approach [4,5]. Detailed investigation on In-Phase and Out-of-Phase power oscillation were carried out in Sweden [6], where the magnitude of autocorrelation function was found to be also different in different fuel assemblies. To explain the situation global and local DR were introduced. Power oscillation was also noticed in pressurized water reactors (PWR) much later, and it was also proposed [6] to estimate a so called modified decay ratio (mDR) to handle the problem similarly to BWR. The fact that the physical mechanism of formation of neutron oscillation has not been totally understood became clear also from the excellent survey of Hagen et al.[7] on two types of instability in natural circulation BWR with potentially different mechanism.

While we believe that both point kinetic [1,2,4] and the extended one dimensional approximation [5] describe correctly the transfer function of the reactor, which have really those feedback effects we also think that one aspects of this phenomena has been neglected until now. Power oscillation is a consequence, it is a measurable outlet signal from the reactor system. Since the outlet it is a multiplication of the reactor transfer function to the inlet fluctuation. Until now there was very little evidence and discussion on the nature of the inlet (temperature and/or density) fluctuation. It was assumed that inlet fluctuation have white (or pink) character and the reactor transfer function is solely responsible for the power oscillation. Oscillation of the power was measured by excore neutron detectors [1,2,4,6,7], sometimes by incore neutron detectors [3,5] and also using top-of core thermocouples. Since those measurements carries information only on power (neutron flux) oscillation, it is not obvious that solely the transfer function, i.e. feedbacks in reactor kinetics are responsible for singularities (for peaks in frequency domain). It is equally possible that the inlet fluctuation has also oscillating character. We shall examine this possibility and we are going to show that that there exist a chaotic oscillation at certain condition on heated and cooled surfaces.

2. EXPERIMENTS

Experiments were carried out with the aim to test new thermocouples suited for incore temperature measurements in research reactors. Since the final aim was to measure transport effect in the water we made an out of pile experiment to test the performance of new thermocouples without radiation effects. An electrically heated rod was placed in a small water tank. We managed to put our thermocouples as near as possible to the heated surface(within 1 mm distance from the surface, but never in touch). The distance between axially placed thermocouple was 8 mm (see Figs.1. and 3.).

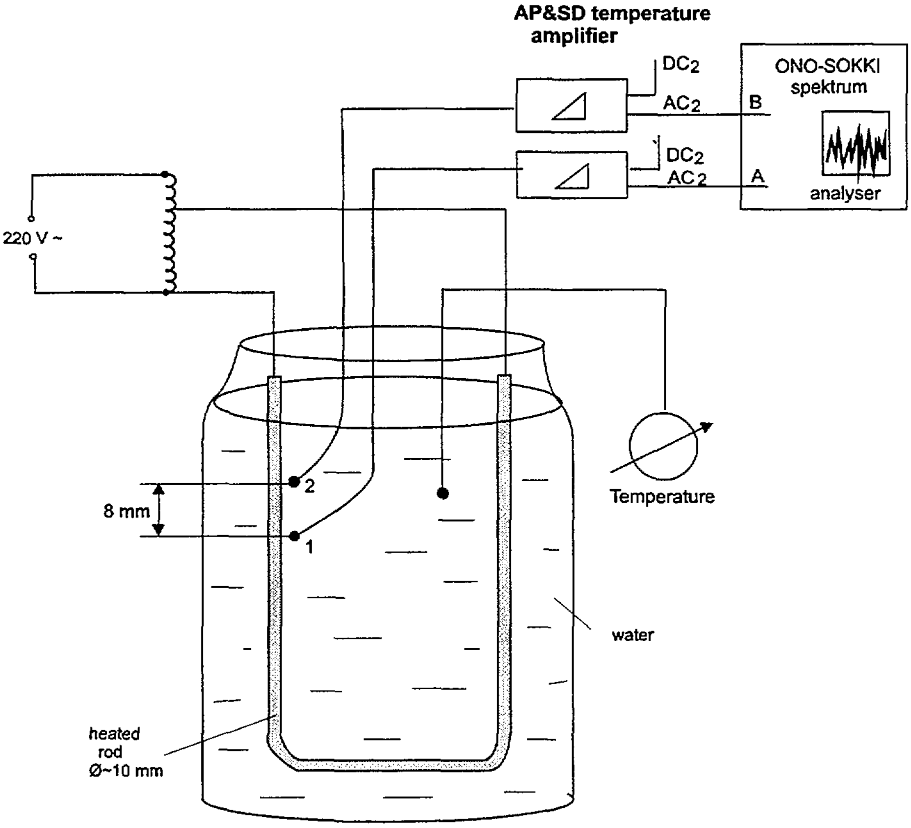

Fig.1. Experimental arrangement

We used a thermocouple amplifiers (AP&SD Ltd.) which enabled us to measure both the temperature as well as the fluctuation of the temperature. Fluctuation as low as 0.01 degree Centigrade were clearly distingushable in the time plot of temperature fluctuation (Fig.2).

Signals were sampled but we also used spectrum analyzer (ONO-SOKKI) for on-line measurement. In this short announcement we rely mainly on results measured by spectrum analyzer. Autopower spectral densities (APSD), phase and coherence were estimated for the two detector signals. Also cross correlation function (CCF) was calculated for different heating rate. A changeable transformer allow us to change the input voltage, thus the electrical power heat-up rate of the heated rod.

3. RESULTS

To our surprise we could observe periodic oscillation in time signals beginning from a certain heating rate to a maximum of that rate (cf. Fig.2.). Below the given heating region and above that oscillation disappeared. Naturally we tested all our equipment about the origin of that oscillation. But we were convinced even more with video pictures taken about the surface of the heated rod (see one picture of that video on Fig.3.)

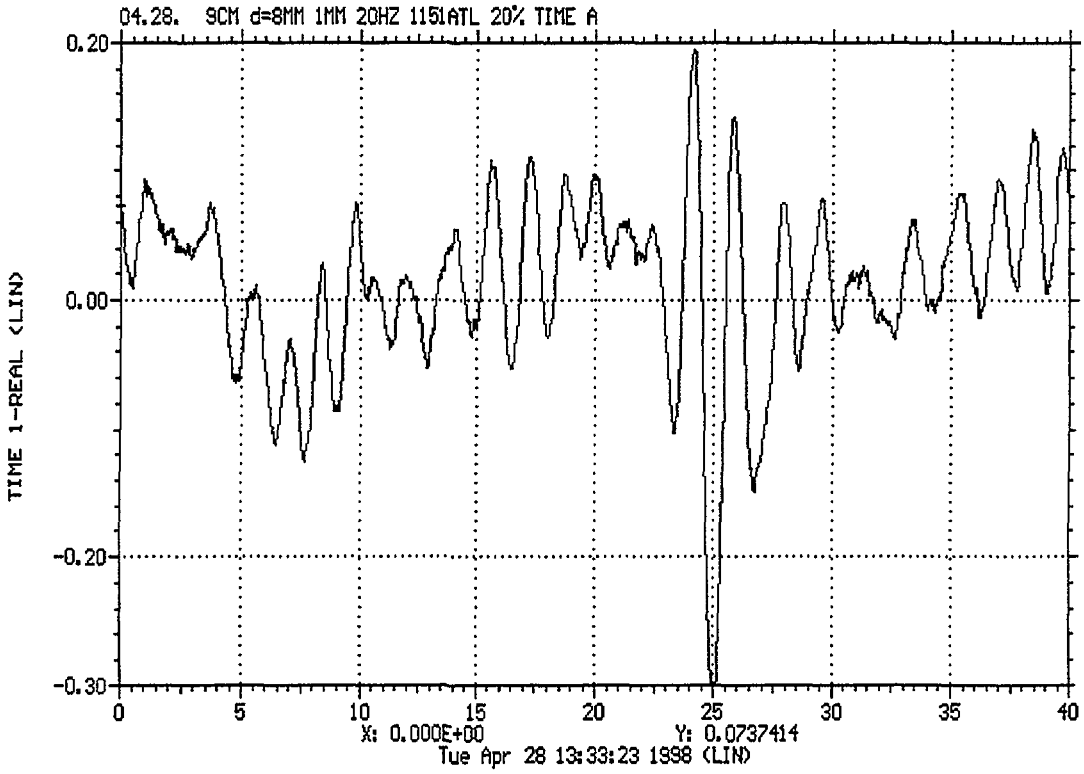

Fig.2. Time signals recorded from thermocouples

On video record one can clearly see the water streaming upward in the vicinity of the surface (within 2 mm distance from the surface). The laminar stream became turbulent at certain heating rate. Turbulence were clearly visible in the form of helical turbulence disattaching from the heated surface. It was even more interesting that they were more or less equidistant when traveling with the water. This helical forms passing the thermocouples gave oscillation character of the temperature signal. We believe it is rather simple to repeat this experiment anywhere.

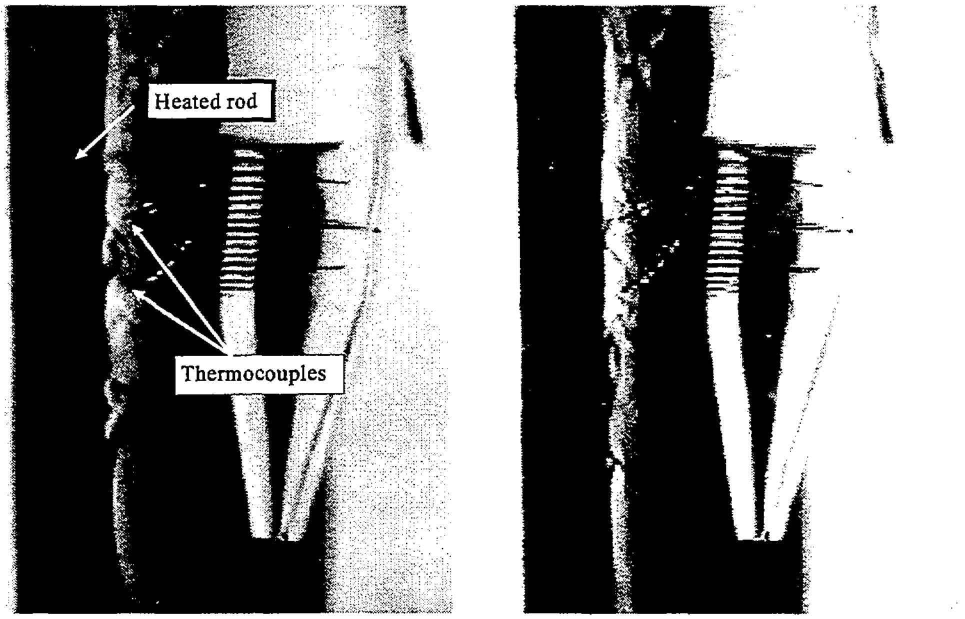

Fig.3. Picture taken from video shot clearly shows helical formation near to heated surface. They travel with the water.

Now if the signal itself has oscillating character, then it is obvious that it must have a resonance frequency in APSD (see Fig.4).

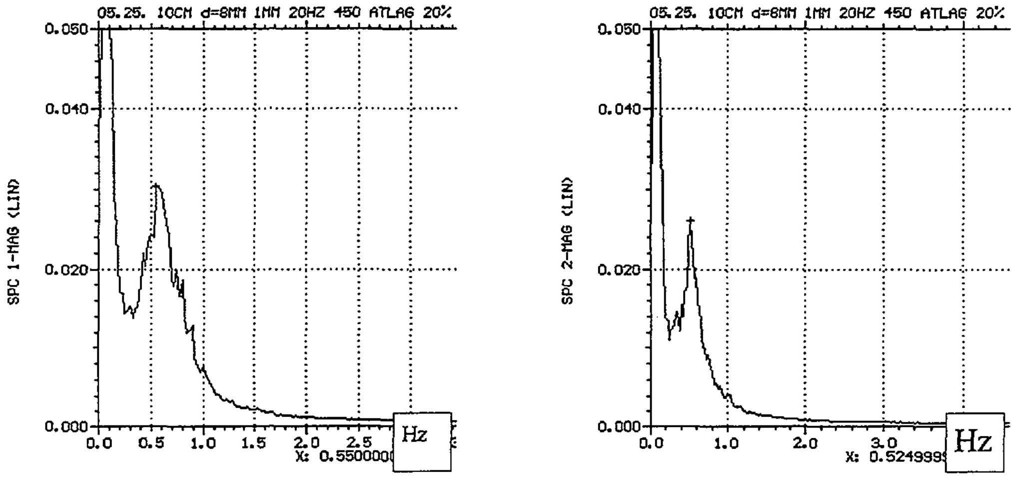

Fig.4. APSD of temperature oscillation with clear oscillation peak

At the same time there were coherence and well defined phase between axially placed thermocouple signals. The linear character of the phase dependence on frequency is well known from the theory of propagating disturbance. Any time delay in two correlated signals will express itself in linear phase dependence on frequency. From the slope of this linear phase function one can define the time delay, and knowing the distance between the sensors the velocity of the water stream can be estimated. It is clear from Fig.5. that the slope of the phase depends on heating rate. Table 1. shows the estimated parameters.

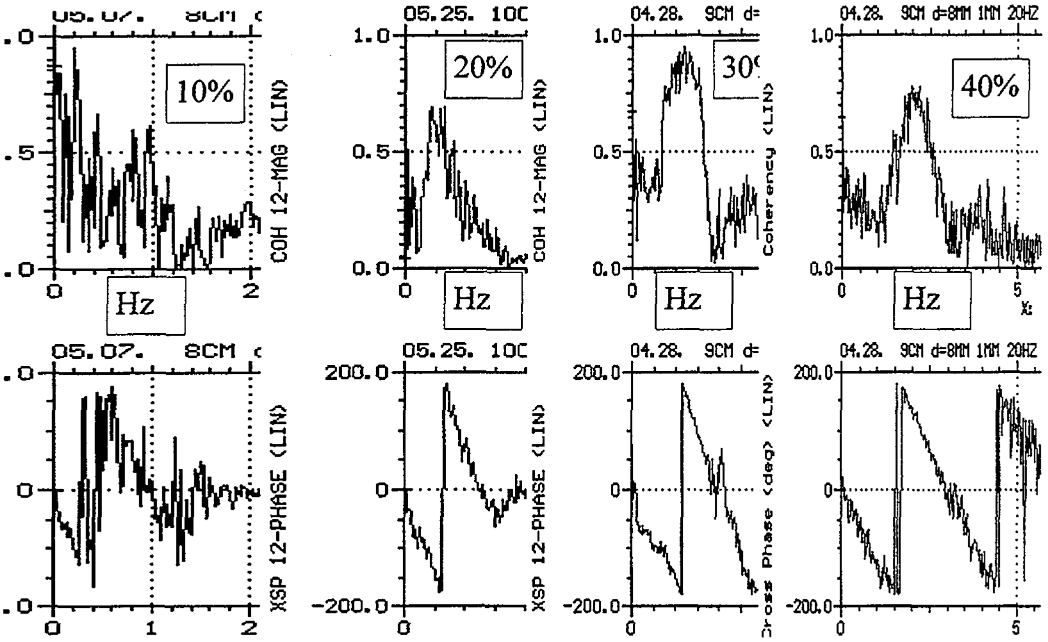

Fig.5. Coherence and phase between axially placed thermocouples at different heating rate

TABLE I. DEPENDENCE OF THE ESTIMATED EIGENFREQUENCIES FROM THE ENERGY SUPPLY OR LINEAR /SURFACE HEAT PRODUCTION

Power in % /Watts	Linear power [W/cm] /Surface power [W/cm2]	CCF maximum [sec]	Frequency from CCF [mHz]	Frequency from Coherency [mHz]	Velocity from CCF [cm/s]
10/ 27.6	0.55 / 2.19	1.2323	231	220	0.649
20/ 80	1.6 / 6.36	0.8102	617	650	0.988
30/ 184.9	3.7 / 14.71	0.4392	1108	1175	1.821
40/ 352.8	7.1 / 28.07	0.3026	2049	2175	2.644
50/ 558	11.2 / 44.4	0.3026	1829	1850	2.644
60/ 845	16.9 / 67.24	0.2562	512	440	3.122

It is also well known that CCF can be also used for time delay estimation. The deviation of the maximum of CCF characterizes the time delay in the signal. Since our signal carries not only stochastic character but it contains also periodic component CCF will also show periodic character as it can be seen on Fig.6.

First of all from the period of CCF one can draw conclusion on the average period of the oscillation of the time signal. This period should be reciprocal to the estimated eigenfrequency of the oscillation from APSD. Comparison and good agreement with the theory can be well seen in Table I. The change of period follows linearly the change of heating power.

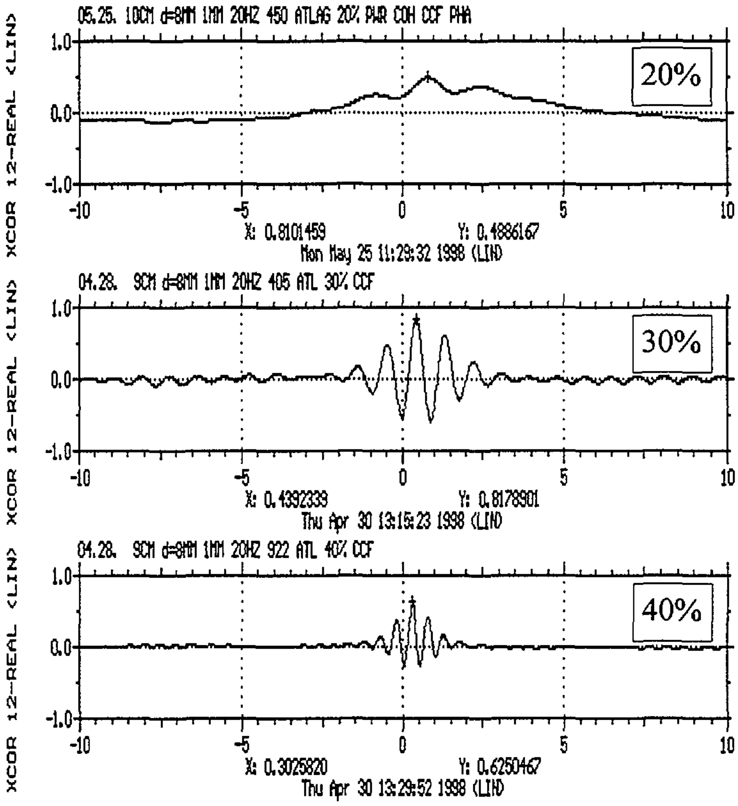

Fig.6. CCF for different heating rates. Observe the different oscillation periods and time delays

4. DISCUSSION

It was observed, that at relatively high power production rate instabilities are formatted on the surface of an electrically heated rod. This shows that at linear heat production larger than 0.5 W/cm (or surface power generation larger than 2.5 W/cm^2) the heat transfer becomes nonlinear and helical forms of turbulence were generated at rather simple circumstances, which lead to oscillation of the temperature field. This new observation is very important for any boiling, heating or cooling process since oscillation of the heat (temperature) near to surface changes the character of the heat removal from the surface of the heated rod. At heat generation larger than 10 W/cm (or 50 W/cm^2) another regime of heat transfer took place, which also had eigenfrequency, but it had stochastic character.

We believe that this is the original cause of the power oscillation in water cooled reactors which has been observed more than 30 years now. In fact investigation of such problems initiated this research as well. We found analyzing our experiment that the oscillation had an eigenfrequency, which linearly depends on the heating power in certain heating range (see Fig.7.). In fact this linearity was observed until (quasi)periodic oscillation took place. When the periodic character was disappearing linearity dropped though there was still a peak in the APSD, - nonperiodic but stochastic nature.

It is well known that the transfer function of the reactor has pole with a frequency of about 1 Hz as well. During the start up of a BWR the heating rate is growing, consequently temperature oscillation might be formatted on the surface of heated fuel rods similarly like in our experiment. The eigenfrequency of such oscillation shifts toward the higher frequencies when the heating rate is growing. Since there is an instability of the transfer function of the reactor system itself at the same frequency region, changing the eigenfrequency of the oscillation with the growing heating one will get resonance of the two function at certain heating condition. This explains the magnitude of this oscillation and also why it is disappearing with further growth of the heating or velocities of the coolant [7].

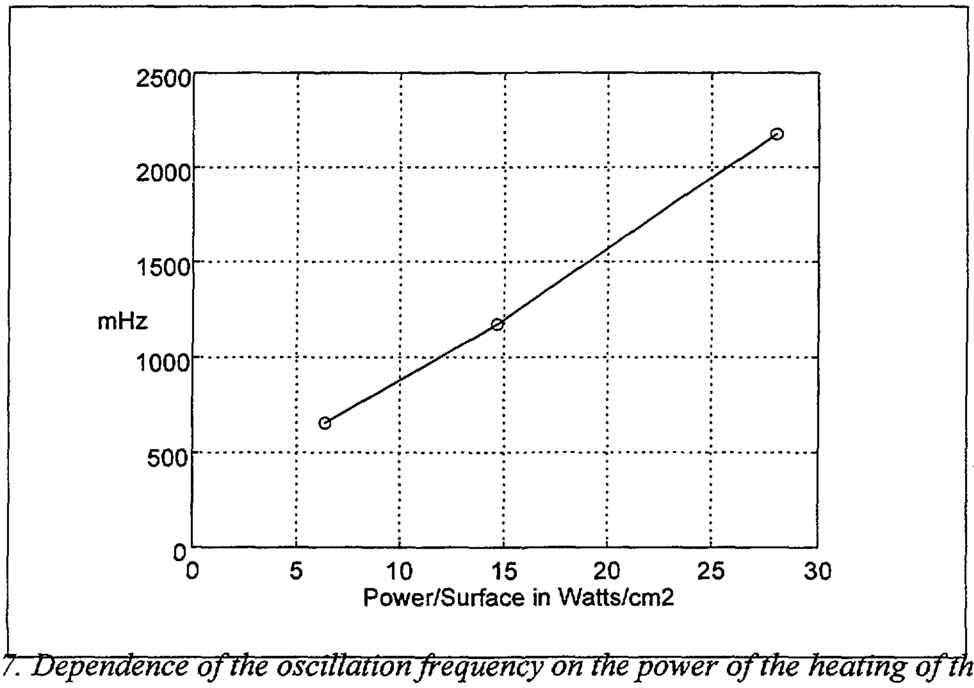

Fig. 7. Dependence of the oscillation frequency on the power of the heating of the rod

The concept of estimating DR widely used today to characterize the instability of BWRs [5] and PWRs[6]. All DR estimation techniques make use from the assumption of white character of inlet fluctuation (inlet in the sense that it is the inlet for reactor transfer function). It is also clear from our experiment that not solely the DR of the reactor transfer function is responsible for power oscillation. Consequently estimation of DR based on such model will overestimate the value of DR thus overestimate the instability of the reactor. Similar conclusion was made in [7].

It is also clear from our experiment why we get sometime power oscillation in case of PWR [5], where nobody has proved until now that the reactor transfer function can have poles. It is connected to the new technology of fuel fabrication, which allows a heat transfer to the cladding so rapidly, that similar oscillation of the temperature field at the surface of fuel pins can take place in PWR as well.

Finally we have to understand, that the reactor core has a strong coupling via neutronic processes. Therefore if we have a temperature fluctuation in one spot it may have effect on temperature fluctuation in another spot. They are connected either in phase (total power oscillation) or in antiphase. This is quite natural if generating noise (temperature oscillation) falls exactly in resonance with the transfer function of the reactor. Here we must understand also, that the period of power oscillation driven by reactivity feedbacks are connected to the coolant transport (time) via the total core, which have a very similar value. Hence the practical method of correction of such problems: one has to avoid (or at least to leave) such resonance situation as fast as possible, either heating further fast (which might be not very easy), or changing the velocity of the coolant.

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