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A COMPLEX NOISE DIAGNOSTIC SYSTEM FOR 1000 MWe PWR WWER TYPE NUCLEAR POWER UNITS

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A complex diagnostic system is presented in the paper. This system was developed for 1000 MWe PWR WWER type reactors but can be used for similar ones. The system consists of three main subsystems: Reactor noise diagnostic system, Vibration monitoring of rotational machinery system and an Acoustic leakage monitoring system. Main characteristics and first experiences are given in the paper.

Pór G.: "KAZMER" A Complex Noise Diagnostic System for 1000 MWe PWR WWER Type Nuclear Power Units KFKI-1992-17/G

KIVONAT

Egy teljesértékű atomerőművi diagnosztikai rendszert ismertetünk röviden. Ezt a rendszert egy 1000 MW-os, nyomottvizes VVER típusú atomerőműben állítottuk üzembe, de a rendszer koncepciója alkalmas más (atom)erőművek számára is. A rendszer három alrendszerre tagozódik: reaktor zajdiagnosztikai rendszerre, forgógépek vibráció diagnosztikájára és az akusztikus szivárgás ellenőrző rendszerre. Bemutatjuk az alrendszerek főbb jellemzőit és az első mérési tapasztalatokat.

"KAZMER"
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ABSTRACT

A complex diagnostic system is presented in the paper. This system was developed for 1000 MWe PWR WWER type reactors but can be used for similar ones. The system consists of three main subsystems: Reactor noise diagnostic system, Vibration monitoring of rotational machinery system and an Acoustic leakage monitoring system. Main characteristics and first experiences are given in the paper.

INTRODUCTION

Noise diagnostic systems have been developed and installed for all four Units (each of them 440 MWe PWR WWER type) of Paks Nuclear Power Station (Hungary) during the last decade by Hungarian firms: KFKI end VEIKI. The complexity of those systems has grown gradually from the Unit 1, where 41 accelerometers, 14 pressure transducer, four ionization chambers and 7 in-core neutron detectors were involved into the first prototype of the noise monitoring system built in 1981. At Unit 2 the number of in-core detectors was enlarged, and also thermocouples were attached to the system. At Units 3 and 4 even more excore and incore neutron detectors, thermocouples were included into a new configuration of the system, at the same time the acoustic leakage detection system having 14 sensors had been attached to the system. The system became fully PC-AT based with on-line data evaluation. These developments served as a basis to develop a new prototype for a new generation of noise diagnostic system for 1000 MWe PWR WWER type nuclear units, which had been purchased by Soviet authorities, and its test is going on at Kalinin Nuclear Power Station.

Ten years of our experience at operating WWER type nuclear power plant units with a growing complexity of noise measuring systems [1] and signal processing methods proved the diagnostic potentials of noise analysis. The basic assumption of the noise diagnostics is that the measured noise signals carry information on process related dynamics, leakage and abnormal vibration in nuclear power plants. Their statistical features can be used for characterizing operating modes, extracting process related parameters and monitoring internal abnormal vibrations as well. The noise measurements and analyses performed at operating NPPs have supported this assumption [1-9]. The performance of the existing noise measuring and analyzing systems developed earlier are encouraging in terms of practical results and applicability.

In this paper we present the main parts, goals and also the first results of the complex noise monitoring, evaluating diagnostic system called KAZMER, which was installed at Kalinin Nuclear Power Station (the nearest nuclear station to Moscow) in 1991. The first part of this paper describes a newly designed reactor noise measuring and analysis system, called KARD, which was developed at the Applied Reactor Physics Department of the Central Research Institute for Physics (KFKI) in Budapest, Hungary. In the second chapter we gave a short overlook of the vibration monitoring subsystem ARGUS-III produced by Institute for Electrical Engineering Research (VEIKI), Budapest, which is now the third slightly modified version of a routinely produced vibration monitoring system. The third part deals with the acoustic leakage monitoring subsystem, called ALMOS, which was developed by Measurement and Automation Department of KFKI, and has a new form at present system. Main characteristic of Kalinin Nuclear Power Station are given in short in the fourth part. Finally the fifth part summarizes those results in headlines, which had been achieved until the present time. The full system was installed during the first half of 1991 and is in full operation only since July, but many good diagnostic results have been gained during the installation as well.

THE "KARD" REACTOR NOISE DIAGNOSTIC SUBSYSTEM

The KARD system [2] is designed for process monitoring, system noise diagnostics and operation related parameter estimation of the reactor itself, and analyses the fluctuating components of process signals (measured by neutron detectors, thermocouples, pressure transducers) from standard instrumentation of reactor core and primary loops. 30 incore neutron detectors, 6 excore ionization chambers, 6 thermocouples 6 pressure transducers and 6 accelerometers from the primary loops are connected directly to the data acquisition system and measured routinely by the automated data sampling and analysis system once a day. The analysis includes not only estimation of the statistical parameters (spectra), but also expert decision on validity of the signals, on the performance of the detectors and also many expertise in diagnostics of the reactor which is listed below. The results are stored for trend analysis performed over the whole fuel cycle. Besides the automated operation using a menu driven interface the user can perform special analyses based on multi channel model analysis.

The main parts of the data evaluation part of the system are:

— basic data processing software to produce statistical functions as Amplitude Probability Densities, Fast Fourier Transformation based spectra, moments,
— knowledge based expert analysis of statistical functions,
— MAR (Multivariate Autoregressive Modeling) based cause-effect analysis of system dynamics, SPRT (Sequential Probability Ratio Test) and spectrum based signal validation and sensor checking,
— daily and weekly storage for a later trend analysis during the whole fuel cycle.

All estimated functions are compared with the same functions of the previous day measurement. Selected functions serve as basis for building a baseline library of statistical functions during the whole fuel cycle.

One of the most important tasks of the automatic analysis part of the system is the analysis of estimated spectra from the point of view of diagnostics of the state of reactor and its inherent processes using the knowledge gained during the experiments of previous years. Extensive theoretical and experimental work has been performed and reported at SMORN conferences , Reactor Noise Meetings, IAEA Symposia and in technical journals [2,3,4,5,6,7,8,9,10]. The knowledge incorporated in the KARD system is used to perform specific tasks.

The main areas of expertise of the subsystem KARD cover:

— Detecting pendular core barrel motion using the cross spectra of noise signals of excore ionization chambers, estimating its magnitude and direction.
— Monitoring the possibility of the existence of in-core vibrating components (control elements) via in-core neutron noise measurements.
— Monitoring the fixation of fuel elements using the change of vibration behavior of fuel elements.
— Monitoring propagating core coolant density fluctuations; estimating in-core coolant velocities in assemblies by analyzing in-core neutron noise signals.
— Detecting possible hot parts of fuel assemblies where the state of coolant became near to subcooled boiling by using in-core neutron noise and regime diagnostic parameters.
— Monitoring Decay Ratio for reactor feedback estimation using ex-core neutron noise.
— Estimating coolant temperature coefficient of reactivity by analyzing core-exit coolant temperature and ex-core neutron noise.
— Estimating pressure coefficient of reactivity by analyzing reactor inlet/outlet pressure and in-core/ex-core neutron noise.
— Estimating time response of temperature sensors using their noise signal.
— Analyzing pressure oscillations and standing waves in the coolant loops and the pressurizer for extracting information on their thermohydraulic state.

The MAR modeling is based on Durbin's recursive algorithm and in the automated system has fixed model order selected from our previous experience, while in the manual system it can be set either manually or by using Akaike's criterion.

A separate module has been developed for calculating the MAR-based residual time series of noise signals and for performing the sequential probability ratio test (SPRT) on the residual time series [10]. The primary objective of applying the SPRT method to the residual time series is to decide if the actually measured noise signals come from the normal state of the process, which was identified in the learning period, or from some other states, regarded as abnormal, (or can be regarded as a new normal state, for which a new MAR model has to be set). The SPRT results in time functions which can be used to detect changes in the measured process or to check sudden changes in the signals with a given confidence level.

For an expert the manual mode of the KARD system gives a multiple possibility to analyze the calculated spectra, to build trends to compare new results with the old ones etc.

THE "ARGUS" VIBRATION MONITORING SUBSYSTEM

Vibration subsystem ARGUS [12] is designed to collect and transfer vibration signal from accelerometers positioned in primary and secondary loops of nuclear power station, to convert these numbers to statistical values, to learn these patterns, to evaluate deviations of actual measured values from previously learned ones, to follow the trends of the measured values, to analyze abnormal behavior using expert shells and incorporated knowledge.

In general the capacity of the ARGUS system is rather large. For example it can be extended up to 792 measuring channels and implemented for any vibration diagnostics [12]. The given representation of this system ARGUS-III has more than 85 channels:

— 32 accelerometers in primary loops

  — 5 on each main coolant pump

  — 3 on the main pipeline of each loops

— 37 accelerometers on the shaft of the turbine

— 16 free inputs for nonstandard measurements plus additional transducers for triggering of the sampling of rotational machines

The conventional system ARGUS has been modified to make possible to attach it to Russian vibrometers (systems: VVK 331 and VSV 301), which are part of the diagnostics at Kalinin Nuclear Power Plant.

This is a the subsystem of the complex system KAZMER, it serves mainly for monitoring the vibration of rotational machines like Main Coolant Pumps (MCP), and Turbines (bearings), but it can monitor the vibrations of main piping system and the feedwater pumps as well.

The main services of the basic software of ARGUS includes:

- Automatic data acquisition, using a menu driven setup
- Two channel spectrum analyzer function for any pair of signals
- Storage of the data and results of the measurements
- Monitoring and evaluation of the state of vibration,
- Built in hardware monitors of the vibration level
- Menu driven filter set
- Synchronized sampling for rotational machinery with maximum sampling rate of 40 kHz

To make the service of the ARGUS more attractive and easier the software system can automatically drive the measurements (the hardware part) and carry out the following automatic measurements:

- SDIAG can make preselected using a menu table automatic measurements at given time of the day, to store them to compare them and also to display and print the results
- REALPRO is a real-time FFT analyzer package
- INDKIF can automatically carry out measurements during run out of rotation machines
- ANALOG checks automatically all functions of the measuring chains and informs the operator on the malfunction
- TDSZR is an expert system for turbine diagnostic.

Monitoring is based on trend analyses using previously learnt data sets and in the given subsystem it includes:

- Defects of unbalance of the shaft
- Defects of coaxillity
- Cracks of the shafts
- Resonances of bearings
- Curvatures in shafts
- Defects of bearings

This list can be widened by the users itself.

Subsystem ARGUS prepared to accept 16 other signal by the definition of the user for nonpermanent measurements as well.

A unique feature of ARGUS-III is the built in expert system [13]. It allows to give hints on the cause of occurrences. The experts system shell called GENESYS 2.1 was developed by a Hungarian firm SZAMALK. The starting knowledge base was collected from experts of Paks Nuclear Power Station filling in a questionnaire which had been compiled by VEIKI experts after four years of experience in vibrational diagnostics of that plant.

THE "ALMOS" LEAKAGE MONITORING SUBSYSTEM

The main aim of the ALMOS [14] subsystem is to monitor and localize the middle range leakages in primary loops when they occur. In this realization of the ALMOS system 20 acoustic emission sensors were installed: 8 sensors near to the top of the reactor vessel; 4 sensors on the hot leg of main pipes, 8 sensors near to steam generators.

Preamplifiers and four-channel units of transmission are distributed inside the containment. The latter serve for transformation of analog signal into their effective value (into their second moments). Signals are transmitted to the main amplifiers and microprocessors where after a selection the start and end position, also the magnitude of the second moment of the burst are transmitted to the computer (IBM-PC-AT), where the final expert analyses of the signals are carried out. The expertise includes:

— Monitoring of the levels of the occurrences;
— signalization when the level exceeds the preselected value;
— finding the place of the leakage, using the information in time delay, and also in amplitudes;
— displaying the current state of the leakage;
— building trends for long range monitoring;
— learning long range patterns.

More details can be read in an other publication at the same IAEA meeting [14].

THE MAIN PARAMETERS OF THE KALININ POWER STATION

Kalinin Nuclear Power Station has two Units in operation and plus two in building process. Each unit is a 1000 MWe WWER type Pressurized Water Reactor. This type has four primary loops, with two main valves, one steam generator and a Main Coolant Pump in each loop.

Main parameters of the Kalinin Nuclear Power Plants are as follows [15]:

— Thermal power: 3000 MWth
— Pressure in primary loops: 16.0 MPa
— Inlet temperature: 286 °C
— Core outlet temperature: 315 °C
— Nominal quantity of the coolant through the reactor: 89000 m^3/h
— Pressure of generated steam: 6.4 MPa
— Steam generation per SG: 1469 t/h
— Type of turbines: K-1000-60/1500
— Nominal power of turbines: 1030 MW
— Nominal inlet pressure: 5.9 MPa
— Type of Generators: TVV-1000-4UZ

— Nominal generated power: 1000 MW
— Output voltage: 24000 V
— Rotational speed: 1500 /min

INSTALLATION OF THE SYSTEM "KAZMER" AT KALININ NUCLEAR POWER STATION

The components of the system had been thoroughly checked in Budapest from the point of view of their main operation characteristics and also using artificial signals and signals collected previously at the operating nuclear power plant by FM tape recorder. After such checking (in which the Russian counterpart also took part, as the first half of the training of operational staff) the system was delivered to the site for installation. The installation of a noise system always carries some difficulties at the power station, because the original signals from the sensors are usually so small that any interference from the high currents can influence on them. The earthling loops can cause also additional problems. Finally there are the plenty of peaks and spectral behaviors which are general for all PWRs, there are such which characterize the given type WWER-1000 reactors and also there are characteristic features of the given unit which can be quite different from other units, and which must be customized before some automatic pattern recognition or alarm system can be placed into effect (cf. automatic core barrel motion warning and alarm level, or vibration of the shaft, or leakage detection).

The installation took almost two months for each subsystem. This includes not only and not mainly just the montage work and the installation processes, but also the search for sources of disturbances. A typical example of the disturbance was the effect of electrical noises on the long cables, in spite the fact that most of the analog signals which were transferred for a longer distance was previously preamplified and transferred into current.

The installation work took a large effort from the utility people, and this period served not only for checking the different functions of different subsystem, but also for a second training period for different possibilities of data manipulation. The knowledge level of operational personal (which consist of highly skilled engineers, in spite the fact that all three subsystem has an automated program for constant measurement) can be demonstrated by their numerous positive suggestion during the installation work. Both the software was modified for the convenience of the user and also many influences of electrical noises and contact problems were solved by utility people. In the same time experiences gained during the installation of the previous four Russian type units helped very much in successful installation.

Most of the knowledge which are inevitable for final automated work of the system can be gained only during a full fuel cycle which may take a year. Therefore the contract consider also a permanent visit of the producer to the power plant in the first year and a modification of the knowledge base of the expert parts of the software packages and also some of the programs at the end of the warranty-year. Nevertheless during the installation work many interesting occurrences has been found which we list in the next chapter,

FIRST RESULTS RETRIEVED BY THE COMPLEX SYSTEM

Here follows a list of the results achieved mainly during the installation period of the whole system. We can submit that in spite the fact that the system started its operation only in this year there are numerous results which say about the capacity and usefulness of the separate subsystems and the whole complex system for diagnostic purposes.

With the aid of subsystem of KAZMER the following results has been achieved during the installation period:

— Detecting core barrel motion in the direction of the loops 1 to 3 with amplitude of maximum 15 microns (by KARD subsystem)

— Detecting small leakage (about 50 l/hours) in a measuring impulse line for pressure transducer (by ALMOS subsystem)

— Detecting incorrect attachment of the neutron channels (only in the noise diagnostic part of the measuring system (using the physical picture from KARD subsystem).

— The core barrel motion has grown up to 45 microns when one of the four main coolant pumps had been switched off. This case showed also that the direction of the motion is determined by the unbalanced pair of loops. This is also a proof of the driving force of this effect.

— The decay ratio has grown up to 0.1 when one of the main coolant pump had been switched off from its normal operational value which was less then 0.01. This also shows the diagnostic value of the decay ration in PWR.

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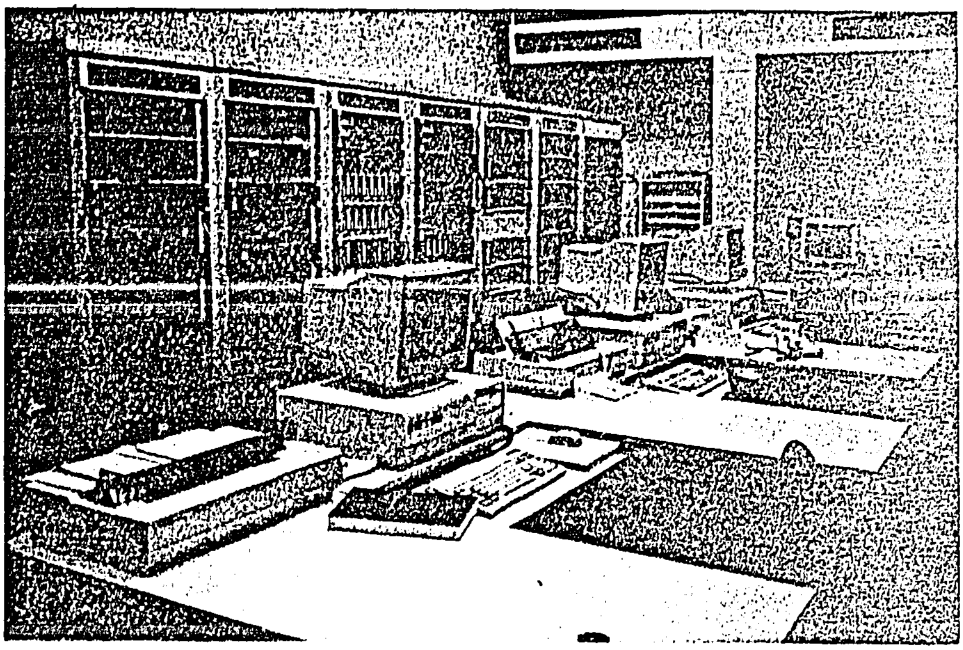


Fig. 1. General view of the "KAZMER" complex noise diagnostic system at Kalinin Nuclear Power Plant

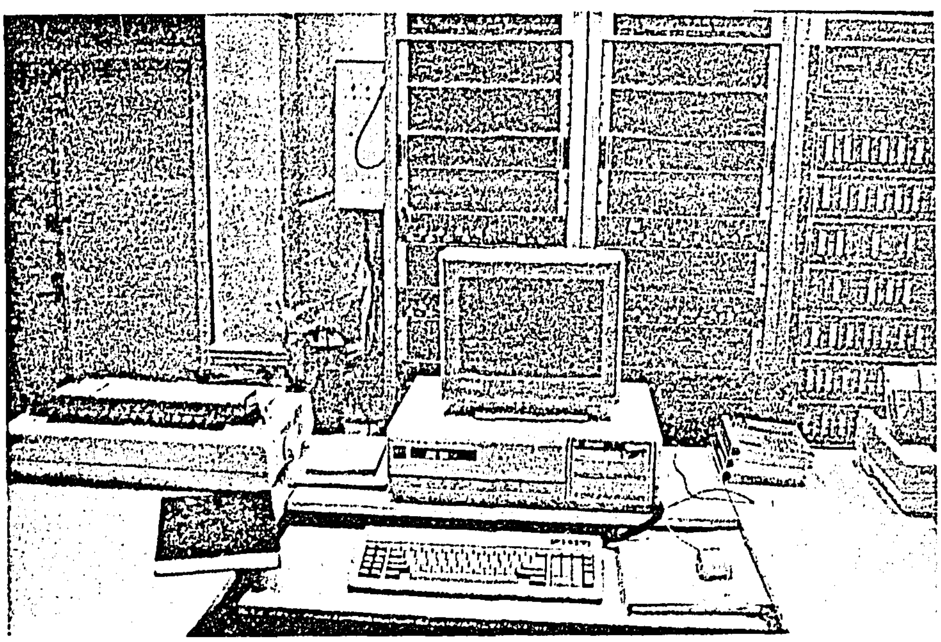


fig. 2. KARD reactor noise diagnostic expert system

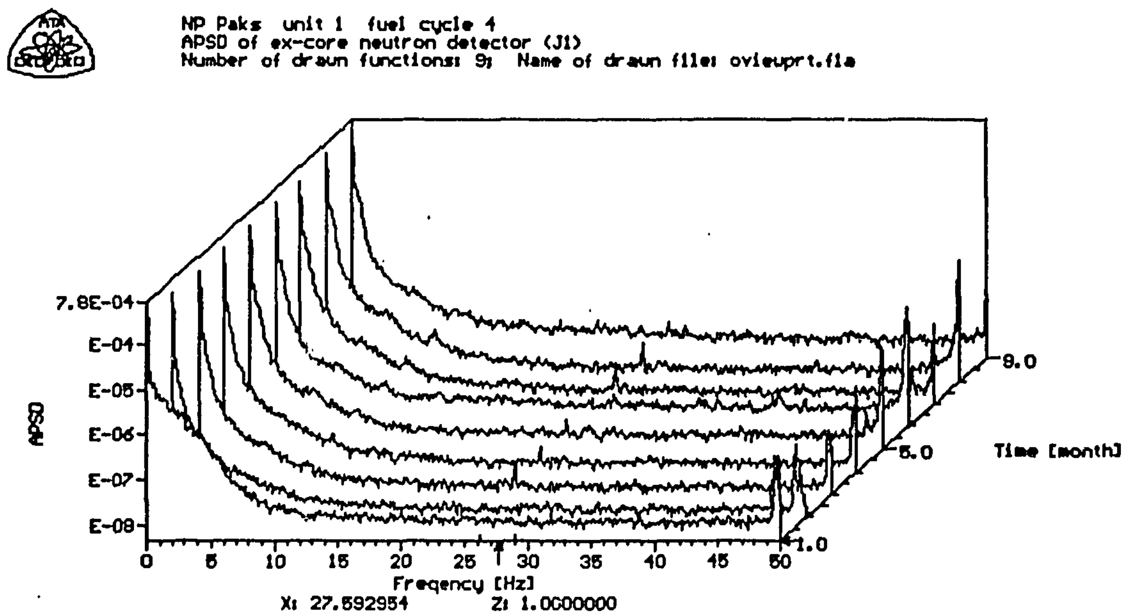


Fig. 3. Variation of ex-core neutron spectrum during a fuel cycle.

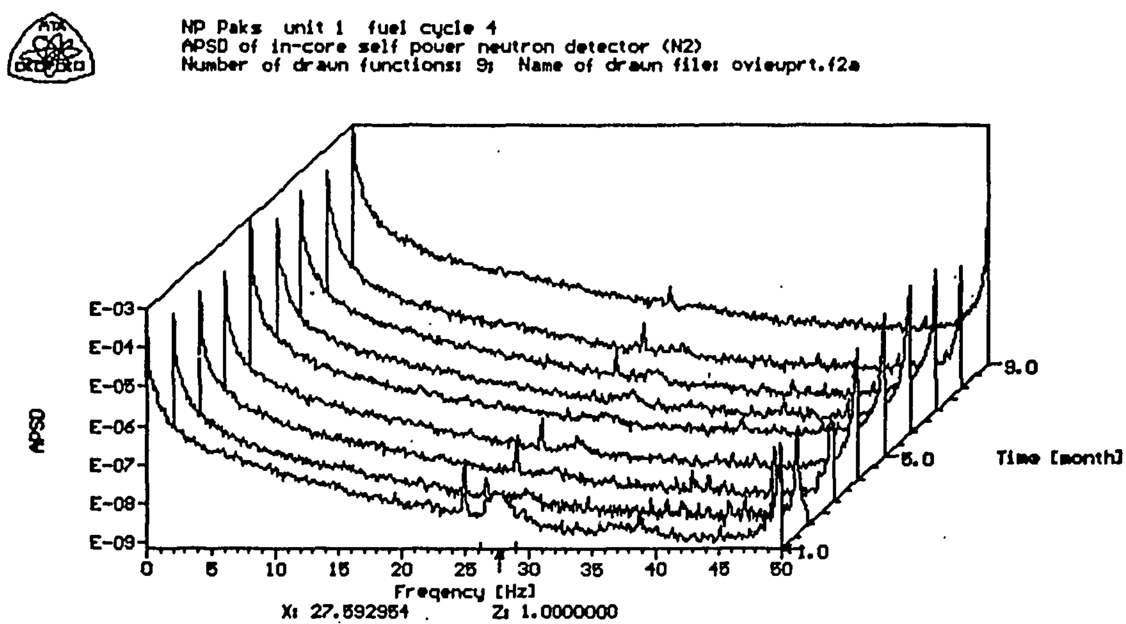


Fig. 4. Variation of in-core neutron spectrum during a fuel cycle.

Looking for trend of one of the peaks

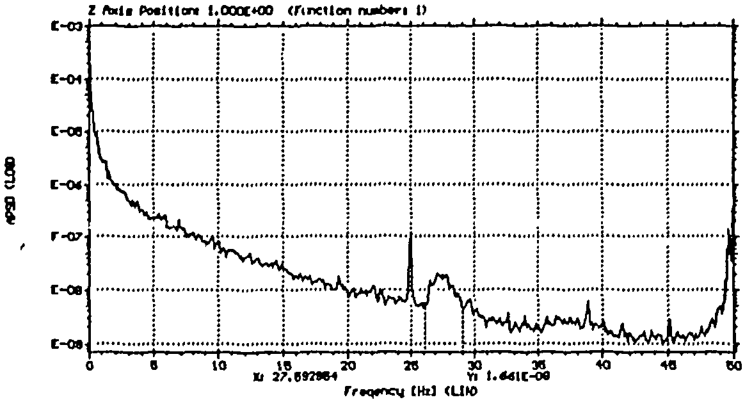


Fig. 5. Selection of the frequency range of the 27 Hz peak for trend analysis.

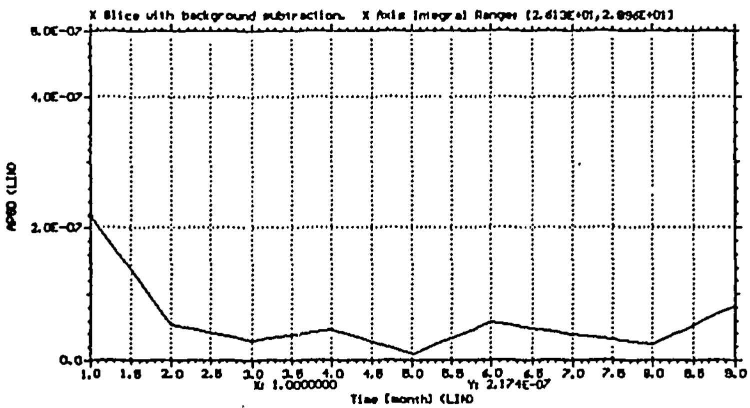


Fig. 6. The change of the selected area during the fuel cycle.

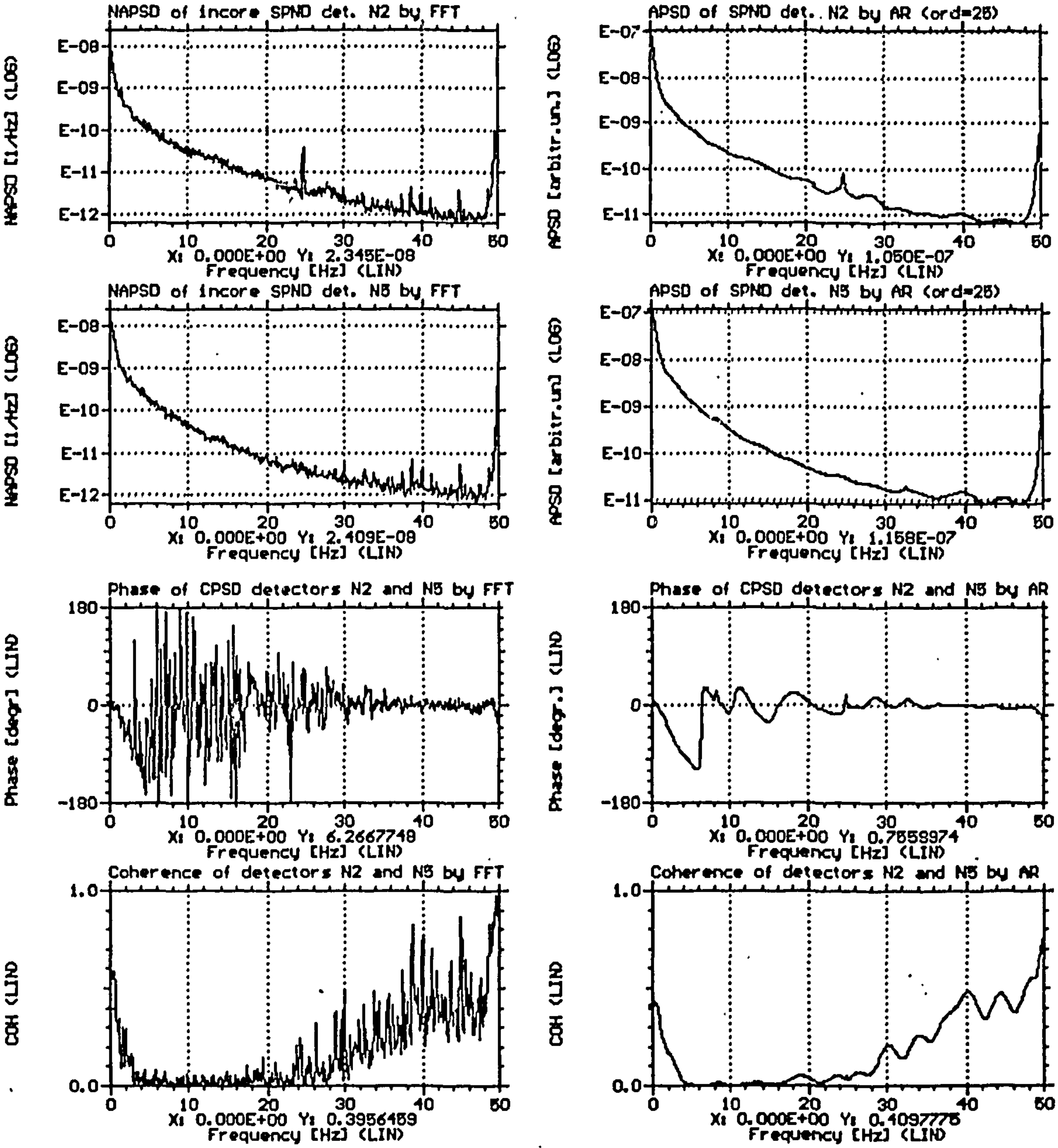


Fig. 7. Spectra estimated by FFT and MAR for in-core neutron detectors above each other.

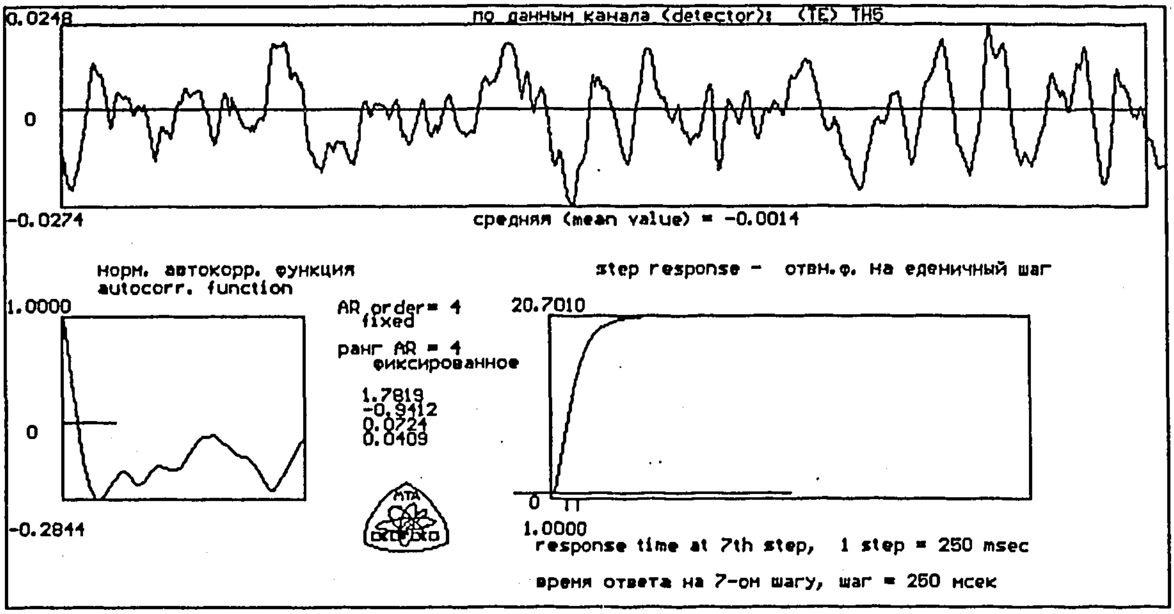
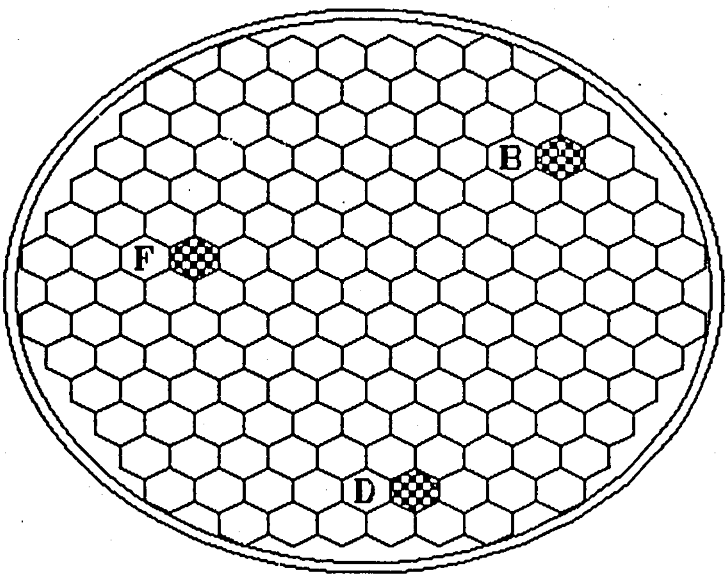


Fig. 8. Response time calculation for a thermocouple using an univariate autoregression model.



F: Пары	Q	D: Пары	Q	B: Пары	Q
F6-F7	60.76	D6-D7	54.39	B5-B6	39.09
F5-F6	43.60	D5-D7	40.43	B1-B3	13.42
F3-F5	32.43	D1-D3	14.65	B1-B5	9.16
F3-F6	19.11	D1-D6	13.33	B3-B6	8.58
F1-F3	16.58	D1-D5	10.66	B1-B6	7.61
F5-F7	16.16	D1-D7	7.71	B3-B5	0.43
F1-F5	13.11	D3-D6	2.59	B6-B7	-
F1-F7	11.45	D3-D7	2.28	B5-B7	-
F1-F6	10.87	D5-D6	2.06	B3-B7	-
F3-F7	8.19	D3-D5	0.04	B1-B7	-

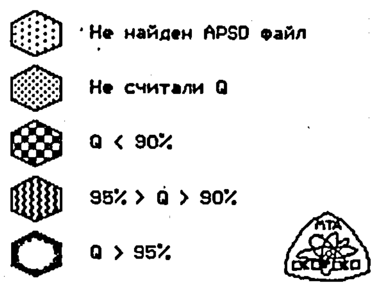


Fig. 9. Presenting level of subcooled boiling in monitored assemblies.

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