ZJE - 172 1976

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# POWER REACTORS OPERATIONAL DIAGNOSIS

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ABSTRACT:

In the article, the definition of the reactor operational diagnostics is presented and fundamental directions of the research are determined. The possible sources of the power reactor malfunctions, the modes of their detection, the data evaluation and the analysis of the results are discussed in detail. With regard to the absence of essential theoretical basis and insufficient in-core instrumentation, the operational diagnostics cannot be presently incorporated into computer-aided reactor control system.

## INTRODUCTION :

With a continually increasing specific load of the core of the second generation power reactors and with an increasing part of nuclear power in the production of electric energy, a necessity of mastering a new branche, so called reactor operational diagnostics, appears. Even though an exact definition of this new scientific branch does not exist at present, it is possible to characterize it briefly as a summary of information about the reactor /including the whole primary circuit/ and about the processes occurring in the reactor, without affecting fundamental safety rules and instructions, including nuclear safety.

Two fundamental groups of works follow from such a conception:

- determination of a dynamic model of the reactor and specification of its parameters;
- establishing, evaluation, interpretation, localization and determination of the degree of the danger represented by the reactor noise sources and its possible linking with the power station control system by means of the digital computer.

The first group represents problems of so-called low-cycle dynamics of the primary circuit as a whole and will not be discussed here. They may be divided into the following subgroups:

- determination of feedback coefficient, determination of time constants
- determination of the transfer function "coolant flowrate → power"
- determination of the transfer function "inlet coolant temperature → power"
- determination of the reactivity of control rods
- determination of the primary circuit constants /e.g. diffusion time/.

The second group of works is very extensive and bears a pronouncedly interdisciplinary character. The main ideas are discussed in the following.

## 1/ Possible sources of power reactor noises at the time of steady state operation.

It is possible to specify the basic types of noise sources as follows:

- the forced circulation of the coolant
- the mechanical vibrations of the core and of primary circuit components
- the fission reaction in nuclear fuel
- the fluctuations of the coolant flow-rate and coolant temperature
- the boiling crisis of coolant
- non-homogeneities in the coolant.

### 1.1 Forced circulation of coolant

This concerns all power reactors. It results in the formation of exciting forces of hydrodynamic and acoustic origin, or in Karman´s vortex street. Mechanical vibrations of the reactor and primary circuit components represent the final effect. Exciting forces of hydrodynamic origin are represented by boundary layer pressure pulsations.

Exciting forces of acoustic origin are such forces, which can be, without remainder, derived from basic laws of mechanics, specially from this part of mechanics referring to technical acoustics. It is possible to classify them as follows:

- the turbulent noise: its frequency spectrum has broad-band character. It is caused by shearing stress /Lighthill´s stress tenzor/ either in the core of the turbulent flow or in the turbulent boundary layer. In ideal case, the power spectral density has a character of "white noise". It can be simulated either by quadrupole /the corresponding acoustic power is $W \sim \varrho \bar{U}^{8} c_0^{-5}$ /, or by dipole /corresponding acoustic power is $W \sim \varrho \bar{U}^{6} c_0^{-3}$ /.

- <u>the acoustic pressure, emitted into the primary circuit or into outer space by circulators:</u> its power spectral density /PSD/ has a broad-band character with sharp peaks at frequencies, corresponding to so-called hydraulic pressure pulsations. The broad-band character of PSD results as a consequence of by-passing of rotor blades, stator blades or another parts by the coolant flow or as a consequence of intensified initial turbulence. Hydraulic pressure pulsations /HPP/ are generated by the non-uniform speed field at the output of rotor blades or by rotor-stator interaction. The frequency spectrum of radial pumps is given by the relation $f_n = n \cdot N_2 \cdot m_s$ and the emitted power level /PWL/ can be expressed by the relation

  $$PWL = A + B \log \frac{Q \Delta p}{N_R} + C \log \frac{N_R}{Q}$$

  Under definite assumptions, which are always satisfied in power reactors, the propagation of HPP in the primary circuit is determined by the wave equation.
- <u>acoustic pressure pulsations</u> /APP/: they are given by eigenvalues of the wave equation solution in cylindrical geometry. The acoustic pressure, corresponding to APP, is given by the relation

  $$p_n = \varrho \frac{\partial \Psi}{\partial t} = i \varrho \omega_{n,m} J_n(\varkappa_{n,m} r)(D_{n,m} e^{-i\gamma_{n,m} z} + E_{n,m} e^{i\gamma_{n,m} z})(G_{n,m} e^{-in\varphi} + F_{n,m} e^{-in\varphi}) e^{i\omega_{n,m} t} \qquad (1)$$

  $$\frac{\omega_{n,m}^2}{c_0^2} = \varkappa_{n,m}^2 + \gamma_{n,m}^2$$

The frequency spectrum is discrete. It may be proved that in primary circuit can be propagated only such APP, frequencies of which are higher or equal to so-called "cut-off frequency", $f^{c}_{n,m}$, given by the relation

$$f^{c}_{n,m} = \varkappa_{n,m} \frac{c_0}{d_0} \qquad (2)$$

Constants $\mathcal{L}_{n,m}$ are tabulated e.g. in /1/.

- acoustic pressure emitted by vibrating component: certain part of exciting energy, which is absorbed by the component from the coolant, is reemitted to surrounding external medium. Mathematically, this effect may be described by simultaneous solution of the equation of component motion and of the wave equation. There exist three basic possibilities for PWR reactors
- vibration of control rods and fuel elements
- horizontal relative movement of pressure vessel and core barrel
- vertical relative movement of pressure vessel and reactor internal components

- standing wave /organ-type pipe resonance/: the question goes about rather specific effect, which occurrs often in the piping section between the circulating pump and reactor or the pump and steam generator or the reactor and steam generator. Calculating the frequency spectrum, the following alternatives can take place:
  - open - closed ends, e.g.

$$f_0 = \frac{c_0}{4L}$$

  - open - open ends, e.g.

$$f_0 = \frac{c_0}{4L}$$

Generally, the frequency spectrum of a primary circuit may be considered as an acoustic system /waveguide/.

A special group of exciting forces is formed by so called Karman´s vortex street, which has the origin in the vortex shedding behind bluff bodies. The frequency of wakes is given by the value of Strouhal´s number $Sh = f d \cdot \bar{U}^{-1}$ which is the function of the Reynold´s number Re. The established experimental dependence for an isolated circular cylinder is shown on Fig. 1.

The special case is the vortex shedding behind tube bundles. The explication of these effects is considerably extensive and it is possible to read about it e.g. in /3/.

## 1.2 Mechanical vibrations of components.

It is evident from the last paragraph that any arbitrary component of the core or of the primary circuit is in fact "submerged" in the field of exciting forces of hydrodynamic or acoustic origin. The interaction results in the vibration of components, which can be described in accordance with contemporary terminology as follows:

- forced, or in the most disadvantageous case, resonant vibration
- self-excited vibration
- self-controlled vibration.

The first two types of vibrations are caused by exciting forces of hydrodynamic or acoustic origin and nearly in all cases have the character of a stationary ergodic random process. The steady state of power station operation is the necessary condition. In the case of the self-excited vibration, the frequency spectrum lies in the band of the lowest characteristic frequencies of the components, while in the case of the forced vibrations the exciting forces are represented by hydraulic pressure pulsations.

The self-controlled vibrations are caused by Karman´s vortex street whose character is generally deterministic; in the range of Re numbers $10^6 - 10^7$ it is stochastic. The component vibrates always with the frequency of separated vortexes and the dangerous state is reached when the vibration becomes resonant. This part is in detail described in /3/.

## 1.3 The fission reaction in the nuclear fuel.

Even in the case of excluding all external disturbances causing noises, the neutron power of the reactor is not constant in time; small, but permanent fluctuations of reactivity occur. The explication of this effect is in the very stochastic nature of the fission and it is not possible to eliminate it in any way.

If all neutrons occuring in a given elementary volume R in various times were uncorrelated, the neutron fluctuation would obey the Poisson's distribution:

$$P_N(R,t) = e^{-\bar{N}(R,t)} \frac{(\bar{N})^N}{N!} \qquad (3)$$

In this case, the variance would be equivalent to the mean value, so that if the distribution of all neutron population in the reactor were Poissoneous in all cases, the study of fluctuations would give information only about the mean value of the neutron flux. However, the fluctuations of the number of neutrons emitted during the fission and the fluctuations of neutron life times cause the non-poissonian noise, whose study at the zero power can give valuable information about kinetic properties of the core.

General theory of the reactor noise is derived from the Chapmann-Kolmogorov equation under the assumption that the process is of Markovian-type. On this basis the balance equation for the probability P /N, C, Z, t + dt/ is derived requiring, that in time t + dt there will be N neutrons and C predecessors and in the interval from 0 to t + dt there will be Z detections.

$$\begin{aligned} P(N,C,Z,t+dt) = {} & P(N,C,Z,t)\{1-[S+C\lambda+N(\Lambda_c+\Lambda_f+\Lambda_a)]dt\} \\ & + P(N-1,C,Z,t)S\,dt + P(N-1,C+1,Z,t)(C+1)\lambda\,dt \\ & + P(N+1,C,Z,t)(N+1)\Lambda_c\,dt \\ & + \sum_{\sigma}\sum_{w} P(N-\sigma+1,C-w,Z,t)(N-\sigma+1)\Lambda_f\,p(\sigma,w)\,dt \\ & + P(N+1,C,Z-1,t)\Lambda_a\,dt \qquad (4) \end{aligned}$$

If F /x, y, z, t/ is a distribution function of a probability distribution P N, C, Z, t/ and f /x, y/ is a distribution function of a probability distribution p /v, w/ and if $f = \sum_{v} x^{v} p(v, w)$, it is possible to write for the case dt → 0 the partial differential equation

$$\frac{\partial F}{\partial t} = (x-1)SF + (x-y)\lambda\frac{\partial F}{\partial y} + \left[\lambda_c(1-x) + \lambda_f(f-x) + \lambda_a(z-x)\right]\frac{\partial F}{\partial x} \tag{5}$$

From this equation it is possible to compute directly particular moments P /N, Z, t/. The first derivatives at x = y = z = 1 lead to the point kinetic equation, the higher order derivatives under the same conditions describe fluctuations of neutrons, of their predecessors and of the number of detections.

In the neutron noise analysis of the random periodical signals, the noise caused by the stochastic character of the fission represents the background.

### 1.4 The boiling crisis.

This disturbance is characteristic for pressurized water reactors. The danger for the operation consists in the fact that reaching the state of the crisis is accompanied by an abrupt reduction of the heat transfer coefficient, which can result in the damaging of the fuel elements. From the view point of diagnostics, the starting point of boiling is accompanied by high-frequency acoustic emission, as a consequence of the implosion of created steam-bubbles. This effect can be registered with a suitable detection device.

The methods of detection of acoustic noises are in an advanced state. The detailed description can be found in /5/.

The crisis of boiling can be detected by means of neutron noises. The most important limiting factor in the case of application of the ionization chamber as a detector are fluctuations, connected with the stochastic nature of the registration process. For the detection of noises the following condition must be satisfied:

$$\sigma_k > \sigma_0$$

where

$$\sigma_0 = \sqrt{(\omega^2\Lambda^2+\beta^2)\frac{2q}{J_0}\Delta f} \qquad \omega = 2\pi f < \beta$$

and noises occur in the frequency region $\Delta f$ of the frequency $f \gg \Delta f$

Detailed experimental research was made by Rajagopal on the light water reactor SAXTON /12/. The application of experimental reactors for some proof measurements is also possible.

### 1.5 The fluctuation of flow rate and temperature of coolant.

At a stationary operating power station the operating state of a circulating pump has not a fixed position on the characteristic, but is fluctuating around some point. This results in the low-cyclic flow-rate changes and in the fluctuations of the fuel element cladding temperature. Finally it results in the variations of the reactor neutron power. This effect is common for all reactor types with the forced circulation of coolant and is discussed in detail in /6/.

### 1.6 Non-homogeneities in the heat transfer medium.

This type of disturbance occurs only in reactors with pressurized water or with liquid metal. In question are rather special cases, caused e.g. by :

- non-homogeneous distribution of the boron acid concentration /in the PWR's/
- occurrence of bubbles as a consequence of insufficient degassing.

The special type of disturbance is so called acoustic emission of materials which is connected with diagnostics of structural integrity of power reactor pressure vessel. This is described in detail in /7/.

By this, the part analyzing fundamental sources of disturbances in the primary circuit can be considered as finished. The following part concerning their registration, evaluation, analysis, localization and determination of the degree of danger will be directed only to the points 1.1 ÷ 1.3.

## 2. The registration of disturbances.

### 2.1 Neutron noise detectors.

The standard equipment of modern power reactors is the in-core instrumentation; for diagnostical purposes the main significance have neutron detectors and eventually gamma detectors. The largest advantage of the utilization of in-core instrumentation for noise analysis lies in the fact that it does not introduce external disturbances into the core. This is necessary from the operational point of view.

The most convenient and most used detectors of reactor noise are ionization chambers, whose power spectral density of the current noise may be written in the following form:

$$S_{IK} = 2g^2 \varepsilon F + 2g^2 F \varepsilon^2 \frac{\overline{\nu(\nu-1)}}{\bar{\nu}^2} |W_0(\omega)|^2 + g^2 \varepsilon^2 F^2 |W_3(\omega)|^2 \sum_i S_i(\omega) \qquad (6)$$

The first term of this equation describes the fluctuations connected with the statistic process of registration in ionization chamber, the second term describes the fission reaction noise and the third one describes the influence of different noise components of the reactor reactivity in the energetic regime. From the same equation it is evident that the relation among the three sources of noise in an ionization chamber is strongly dependent upon the effectiveness $\varepsilon$ of the detector. When the standard location of chamber in the control system is used it is possible /under assumption $\varepsilon \ll \beta^2$ / to neglect the second term in the comparison with the first one so that in the energetic regime dominates the third term.

Very promising detecting elements which find ever broader application in in-core instrumentation systems of power reactors are so called self-power neutron /SPN/ detectors, sometimes called after their discoverer the Hilborn´s detectors.

From the neutron noise diagnosis standpoint the most attractive detectors are so called SPN detectors with prompt response. Their output current is generated by electrons from Compton effect and photoeffect, induced by prompt gamma quants from /n, $\gamma$ / reaction in in cobalt or platinum emitters. The response time of this detector is limited only by the frequency response of the measuring circuit. It is possible to use the SPN detectors with vanadium emitter developed by "SODERN". The current in this detecting element is caused mainly by beta-particles which are emitted from the activated nuclei. In this case the response time is determined by the half-life of $V^{52}$ which is 3.76 minutes. However, the formed compound nucleus emits immediately after the neutron absorption a gamma quantum producing neutrons by Compton effect and photoeffect. In the core of the power reactor the emitter ejects the following electrons by the same physical mechanism, mostly caused by the prompt gamma radiation from the fission. The two last effects are prompt, so that the resulting sensitivity of vanadium SPN detector from the dynamical standpoint is composed from both delayed and prompt parts. The prompt component in common types forms about 5% of the delayed one. Entirely analogous mechanism occurs in rhodium SPN detectors. Half-life of $Rh^{104}$ is 42 sec but in comparison with vanadium SPN detector it has substantially higher burn-up /3.9% per month/, while that of vanadium is only 0.12% per month and of cobalt 1% per month in the thermal neutron flux $10^{14}$ n/$cm^2$s. From the above mentioned reasons the vanadium SPN detector is very perspective detecting element for in-core instrumentation and its power spectral density at the frequencies $f \gg$ 0.08 Hz has the same shape as a power spectral density measured with cobalt SPN detector.

Besides from the neutron flux it is possible to obtain information about the state of the reactor also from the prompt gamma radiation. The advantage of noise analysis of prompt gamma quants may be in the fact that thanks to greater free path of gamma rays their detector is evidently less sensitive to local effects than neutron detector and a suitable construction of scintillation detector can secure the discrimination of undesirable effects caused by the gamma quants from fission products. For the routine measurements the noise analysis of gamma quants is not used till now.

## 2.2 The classical detector elements.

For the determination of other sources of disturbances the following common types of detectors are used:

- a sensor of pressure pulsations with frequency range 0.1 Hz and higher
- an accelerometer with the same frequency range
- strain-gauges
- microphonee /for the detection of the noise radiated e.g. by circular pump to the external environment/
- the thermocouples with very low time constant.

Thus the matter concerns available commercial types. Considering that the most of these detecting elements would work for a long time in the high neutron flux, it is necessary to solve the question whether their exposure does not influence their sensitivity.

## 3. The evaluation of measured quantities.

After registrating a disturbation signal by some of the above-mentioned detectors it is preamplyfied or the undesirable frequency band is filtered off. Further processing must account for the fact that in the steady state conditions the analyzed effect bears a character of a stationary ergodic random process and so the spectral analysis is to be performed in a real time scale. Alternatively, the self-correlation or mutual-correlation functions or power spectral densities must be determined.

The contemporary state of measuring techniques gives three basic alternatives of the evaluation. The simplest equipment is composed of the classical devices which treat the signal by the analogue way. The main elements are the broad-band or narrow-band frequency analyzer and the level recorder. The transition to the required power spectral density will be performed either by conversion of measured data in accordance with defining relation or by complementing the measuring system by a suitable filter. If the correlation functions are required, then instead of the analyzer and the recorder some standard types of correlators are used. The disadvantage of the described way is the small accuracy of the measurement /we can never establish instantaneous spectral density/, the long evaluation time and, moreover, we must add the subjective affection of the measurement by the experimentator.

The further measuring alternative is represented by the hybrid system treating the signal in an analog-to-digital way. The instrumentation consists of the analog-to-digital converter /if possible with auxiliary memory/, of the digital computer with high-speed printer and of the spectral analyzer working in the real time jointed parallelly to it. The system conceived in this way has a number of advantages against the preceding one, e.g.:

- the spectral analyzer makes the visual control of the watched process possible, including the decision following from it, which part of the process is interesting and has to be analyzed in more details
- the digital part with the help of suitable algorithms evaluates the measurements in the off-line system.

The third alternative is made by the single-purpose hybrid systems which perform at least the third-of-octave or narrow-band frequency analysis in the real time. In addition to it, they may with the help of the standard programs compute the correlation functions, power spectral densities, mean square values and so on. The typical examples are spectral analyzers 3347 and 3348 of the firm Brüel and Kjaer or the Fourier analyzer of the firm Hewlett-Packard. These instruments perform on-line analysis.

## 4. The interpretation of the results of measurements and localization of the disturbation sources.

In fact these problems make the heart of the operational diagnostics and from the preceding its complex character is evident. On the basis of the contemporary state of the knowledge it is, though, possible to create a certain type of the mathematical and physical model for the interpretation, but its significance is only methodical. In practice it is always necessary to respect the differences of the individual types of power reactors /their constructional design and arrangement of the primary circuit/, which will influence the choice or the preference of the certain type of the sensor.

The fundamental assumptions for the design of the model are:

- the investigated process is random, stationary and ergodic
- the dynamical properties of the reactor /from the point of view physical, mechanical and acoustical/ may be expressed by the corresponding transfer function
- it is possible to express mathematically the power spectral density of the disturbation sources according to 1.1 - 1.3.
- the response of the reactor as a dynamic system to the input disturbations is both definable mathematically and verifiable experimentally. It means that there exist non-zero values of the power spectral density $\phi_j(\omega)$ of the neutron flux, coolant pressure pulsations, core component vibrations and the radiated noise.

Then it is possible to write

$$\sum_{j=1}^{N} \phi_j(\omega) = \sum_{j=1}^{N} |W_j(i\omega)|^2 S_j(\omega) \qquad (7)$$

The concrete expressions for the corresponding pairs $|W_j(i\omega)|^2$ and $S_j(\omega)$ are following:

- the mechanical transfer function of the core components or of the primary circuit components

$$|W_1(i\omega)|^2 \sim \frac{1}{[(\omega_n^2-\omega^2)^2+(2\xi_n\omega_n\omega)^2]} \qquad (8)$$

$S_1(\omega) = const$ ... the broad-band noise

$S_1(\omega) \sim \delta(\omega_m-\omega)$ ... acoustic and hydraulic pressure pulsations, radiated acoustic pressure

- the acoustic transfer function of the primary circuit including the reactor

$$|W_2(i\omega)|^2 = f(Ma, \omega, \ell)$$

$$S_2(\omega) \sim \delta(\omega_m-\omega)$$

The concrete form of the function $|\varphi(Ma,\omega,l)$ is considerably complicated and is dependent on the design of the primary circuit.

In more details it is possible to learn about the derivation of $|W_2(i\omega)|^2$ in /9/.

- The transfer function of the reactor core with zero power is given by the relation

$$|W_2(i\omega)|^2 = \frac{S_n(i\omega)}{S_k(i\omega)} = \left| \frac{N(0)}{\Lambda} \, \frac{\prod_{j=1}^{6}(i\omega+\lambda_j)}{\prod_{j=1}^{6}(i\omega+r_j)} \right|^2 \qquad (9)$$

where $r_j$ of the transfer function poles are defined by

$$\prod_j (i\omega+r_j) = \prod_j (i\omega+\lambda_j) + \frac{1}{\Lambda}\sum_{j=1}^{6}\beta_j \prod_{j-1}(i\omega+\lambda_{i-1}) \qquad (10)$$

The reactivity changes are the input disturbations in the equation /9/. The various technological processes act on the power level by means of the temperature reactivity coefficient, so that the reactivity noises preceed the power noises. Further, the reactivity is affected by the random vibrations of the reactor construction components, especially of the regulating rods and fuel elements. Roughly it is possible to say that the vibrating absorber is more effective than the stationary one, but the vibrating fuel element causes the increasing of the thermal utilization coefficient; the increase reactivity acts as a positive feedback /10/.

The practical experiences show that by analyzing the arbitrary output signal by one of the three above mentioned methods it is very difficult to localize the source of disturbation. Installation of strain gauges or of the accelerometers in the reactor vessel is not possible for safety reasons, so that the only source of information about the processes in the core are the in-core sensors or the pressure transducers if they are installed. Thus if the resonance appears in the neutron flux power spectral density, it is not possible to determine with certainty whether the resonance is caused by the change of $|W_3(i\omega)|^2$ or of $S_3(\omega)$. Analogically, analyzing the power spectral density of coolant pressure pulsations enables to localize with certainty only the circulating pump as a source of hydraulic pressure pulsations.

From these reasons one makes use of the cross correlation functions or the cross power spectral densities. One of the signals is always from the in-core sensor, the other either from the pressure transducer, the thermocouple, the microphone or the accelerometer, which can be installed somewhere on the reactor vessel.

By this the possibilities of so called "passive" localization of disturbation are worked out. The nature of the "active" localization is in an artificial production of disturbations in a manner which does not disturb normal operating conditions. In the course of it oscillatory measurements and noise analysis are being completed. The oscillatory measurement leads to the determination of the transfer function and the noise analysis gives a possibility of the determination of the power spectral density of the reactivity fluctuations /13/.

## 5. Determining the degree of danger of the disturbation.

Let us suppose that the disturbation in the reactor is localized by some of the above-mentioned methods. For the operational safety it is necessary to determine its admissible value and to estimate or measure the possible consequences of the potential excess. In the first phase, the results of the analysis of the analogue or analytical computational methods are applied. The results of the dynamic measurements from the complex reactor testing period will have also a great weight, if they were properly projected and performed. In this period it is possible to perform for example some tensometric measurements in the core. The conclusions from the experiments on the non-active loops or on the research reactors, where it is possible both to generate the disturbation and to analyze its response will have of course the definite word. It is necessary to pay attention to the extrapolation of the obtained results. It is necessary to take into consideration that nearly all occurring processes are stationary, random and ergodic. It means that the applied test equipment must be either in the scale 1:1 /e.g. full-scale model, which is sometimes considerably expensive/ or it is necessary to have theoretically well-founded and experimentally verified laws of model similarity. Thus, the works of this type need the team work of the theoreticians, experimentators and the owner of the station in any case.

The juridical aspects of the noise measurements are worth of mention, too. The contemporary level in the area of the noise measurements interpretation in the world does not give possibilities to accept criterions for the intervention of the operator in the case of on-line reactor noise detection, to say nothing of the automatic intervention of the safety and regulation system in the course of possible on-line processing of the noise signals. In this case, the responsibility of the operator who gathers measured data is not clear in the case that after-the-breedown analysis of the noise data shows a change of the power spectral density in the time period correlated with the breakdown. The obligation of the operator to stop the power station and to cause possibly considerable financial losses in the case that noise analysis shows unexplainable but conspicuous changes which cannot be correlated with other monitored variables cannot be specified at this time.

## CONCLUSION.

This article intended

- to make clear the term "power reactor operational diagnostics"
- to qulify the basic trends of works
- to point out the mutual coupling of the separated partial problems.

Conclusions derived from it may be formulated as follows:

- the operational diagnostics has an interdisciplinary character and may be persued only by a team-work of experts in the fields of mechanics, nuclear physics, thermomechanics, instrumental and computational techniques
- required diagnostical measurements must be usually planned already during the projection of the nuclear power station
- the diagnostics cannot be accomplished without a modern evaluating technique
- because influences of many disturbances /e.g. of vibrations of fuel elements or regulation rods/ on reactivity changes are not cleared up till and owing to the insufficient setting of the reactor by detectors and due to the lack of data about their behaviour in high neutron fluxes, operational diagnostics cannot be in the present linked up with the system of reactor control by the digital computer and a long and international work will be needed before this idea turns into reality.

## List of symbols.

| | |
|---|---|
| A,B,C | constants for a given type of a circulating pump |
| $c_0$ /$\mathrm{m\,sec^{-1}}$/ | sound velocity |
| $d_0$ /m/ | diameter of cylindrical pipe |
| D,E,G,H | integration constants |
| f /$\mathrm{sec^{-1}}$/ | frequency |
| F | mean number of fissions |
| $i = \sqrt{-1}$ | |
| j | index |
| k | reactivity |
| l | characteristic dimension |
| n,m | modal numbers |
| $N_R$ | number of rotor blades |
| $n_s$ | number of revolutions per sec. |
| P /$\mathrm{Nm^{-2}}$/ | acoustic pressure |
| $\Delta$ P /$\mathrm{Nm^{-2}}$/ | pressure loss |
| Q /$\mathrm{kg\,sec^{-1}}$/ | flow rate |
| q /C/ | mean charge released from detector after the registration of one neutron |
| r /m/ | radial co-ordinate |
| t /sec/ | time |
| u /$\mathrm{m\,sec^{-1}}$/ | mean velocity of the coolant |
| x,y,z /m/ | co-ordinates |
| $\alpha_{n,m}$ | modal constant |
| $\beta$ | delayed neutrons rate |
| $\beta_j$ | the rate of the j-th group of delayed neutrons |
| $J_0$ /A/ | ionization chamber current |
| $\gamma_{n,m}$ /$\mathrm{m^{-1}}$/ | axial wave number |
| $\delta(\omega-\omega_n)$ | Kronecker's delta |
| $\varepsilon$ | detector efficiency /number of readings per fission/ |
| $\lambda$ | probability of predecessor's delayed neutron emission in time unit |

| | |
|---|---|
| $\varkappa_{n,m}\ /m^{-1}/$ | radial wave number |
| $\lambda_j$ | decay constant of the j-th group of delayed neutrons |
| $\Lambda$ | life-time of prompt neutrons /sec/ |
| $\Lambda_c$ | probability of neutron capture or escape in time unit |
| $\Lambda_f$ | probability of inducing a fission by neutron in time unit |
| $\Lambda_d$ | probability of neutron detection in time unit |
| $\bar{\nu}$ | mean number of neutrons released by one fission |
| $\nu\ /m^2/sec/$ | kinematic viscosity of coolant |
| $\xi_m$ | generalized damping coefficient |
| $\rho\ /kg \cdot m^{-3}/$ | density of coolant |
| $\sigma_k$ | departure of reactivity fluctuations caused by the boiling |
| $\varphi$ | angle coordinate |
| $\phi$ | potential function |
| $\omega\ /rad \cdot sec^{-1}/$ | angle frequency |
| $Ma = \frac{\bar{U}}{c_0}$ | Mach number |
| $N\ /t/$ | neutron density at time t |
| $N\ /0/$ | neutron density at time 0 |
| $N\ /R,t/$ | mean number of neutrons in volume R at time t |
| $p\ /v,w/$ | probability of creation of v prompt and w delayed neutrons by one fission |
| $P_N\ /R,t/$ | probability of being exactly N neutrons in volume R at time t |
| $S_j\ /\omega/$ | power spectral density of the j-th source of disturbance |
| $W_0\ /i\omega/$ | transfer function of the fissionable medium of the zero-power reactor core |
| $W_1\ /i\omega/$ | mechanical transefer function of the component |

| | |
|---|---|
| $W_2 /i\omega/$ | acoustic transfer function of primary circuit<br>including the reactor |
| $W_3 /i\omega/$ | transfer function of the reactor in a given power regime |
| $\frac{\overline{\nu(\nu-1)}}{\bar{\nu}^2}$ | so called Diven´s factor |

## Literature.

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