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OPTIMIZATION OF CONTROL SYSTEMS BY AN ANALOG METHOD

by

A. GARRONI and A. LUCIA

1968

Joint Nuclear Research Center
Ispra Establishment - Italy

Reactor Physics Department
Research Reactors

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Particular reference is made to nuclear reactors, in which hypotheses and techniques of this type play a particularly important part. Lastly, by way of a concrete example, the results for the ISPRA I reactor are given.

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SUMMARY

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KEYWORDS

FEEDBACK
CONTROL SYSTEMS
ANALOG SYSTEMS
DIFFERENTIAL EQUATIONS
SIGNALS
OPTIMIZATION
NOISE
ISPRA-1

CONTENTS

1) INTRODUCTION

It frequently happens that dead zones are introduced into the feedback chain of a control system in order to compensate the effect of random perturbations of minor importance. The calibration of these dead zones is normally performed experimentally by an operator who has to make a compromise between a number of requirements, such as accuracy, the load on the control system, power consumption, wear and tear of moving parts, etc...

From this practice whose shortcoming consists in the wide margin left to individual judgment, it is possible to devise a stricter method which, while avoiding the drawbacks of a direct mathematical solution, monetheless represents a sufficiently valid and general approach to the problem.

The method, which is mainly applicable to steady-state systems subject to perturbations which are likewise stationary, can be used for optimizing the response in working conditions with constant references. In general the optimization of the system will consist in the minimization of an overall functional given by the equation:

$$Q = K_1Q_1 + K_2Q_2 + \dots\dots\dots\dots K_nQ_n \qquad (1)$$

where the constants K_i relate the values Q_i of various functionals.

By considering, for example, the accuracy requirement already mentioned above, and understanding as such the greater or lesser displacement of the values effectively assumed by certain variables $S_i(t)$ of the system from the respective values required S_{io}, it is possible to define a certain number of terms of the functional Q as quadratic means of these displacements:

$$\lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{T} (S_i(t) - S_{io})^2 dt \qquad (2)$$

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The load on the control system can, on the other hand, be evaluated and taken into account on the basis of the average number of interventions per second:

$$\lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} n(t)dt \tag{3}$$

where $n(t)$ is the frequency of intervention and equation (3) relates to material fatigue phenomena rather than to considerations of maximum stress.

Finally, for the power consumption and wear and tear of moving parts, terms can be used of the type:

$$\lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} w(t)dt \tag{4}$$

where $w(t)$ indicates the power required by the control system, or that dissipated by the mechanical parts whose wear and tear is checked.

Limiting ourselves to these cases, the final result is a functional of the type:

$$Q = \sum_{i=1}^{m} \lim_{T\to\infty} \frac{K_i}{2T} \int_{-T}^{T} (S_i(t) - S_{io})^2 dt + \sum_{j=m+1}^{m'} \lim_{T\to\infty} \frac{K_j}{2T} \int_{-T}^{T} w_j(t)dt +$$

$$+ \lim_{T\to\infty} \frac{K_{m'+1}}{2T} \int_{-T}^{T} n(t)dt + \ldots\ldots\ldots\ldots\ldots\ldots + K_n Q_n \tag{5}$$

in which the various quantities $S(t)$, $w(t)$, $n(t)$ are functions ot the time related to the perturbations and, like these latter, of a random and stationary type. Further development of the expression (5) in the sense indicated by the present article would require the use of a mathematical model of the system to be optimized.

2) THE OPTIMIZATION FUNCTIONAL IN THE CASE OF NUCLEAR REACTORS

The optimization of the steady state response is particularly important in nuclear reactors, especially power reactors, for which the norm consists in steady-state operation, as in the nuclear power stations, always used as base-load power plants.

As regards the parameters to be taken into account in the functional to be minimized, note should be made of the importance in a nuclear plant of the power produced and the operating temperature. The reactor power is directly related to the thermal gradients in the core components and in particular in the fuel; the operating temperature is on the one hand an indication of the usability of the energy produced, and on the other hand is related to the degree of thermal stress on the materials. Both parameters are related to the technological operating limits of the plant, and the fluctuations in them with respect to the required values make it necessary to adopt safety coefficients prejudicial to operating economy. Hence the importance of minimizing these fluctuations.

Taking $P(t)$ and $T(t)$ as the power and the temperature respectively, and allowing for the mean quadratic value of the variations with respect to the desired value, as seen in (2), the first summation in the second member of (5) is expounded as the sum of the following two terms:

$$K_1 Q_1 = K_1 \lim_{T\to\infty} \int_{-T}^{T} (P(t) - P_o)^2 \, dt \qquad (6)$$

$$K_2 Q_2 = K_2 \lim_{T\to\infty} \int_{-T}^{T} (T(t) - T_o)^2 \, dt \qquad (7)$$

The next most important considerations, in nuclear reactors, are problems relating to the wear of moving mechnanical parts, which when situated in areas subject to heavy irradiation cannot be easily or quickly replaced. This applies in particular to certain parts of the control rod mechanisms; their wear and tear is generally attributable to forms of coulomb friction: it is then proportional to the power dissipated on the supports, which can be expressed by the equation:

$$w_j(t) = h_j \mid v_j(t) \mid \tag{8}$$

where $v_j(t)$ is the instantaneous velocity of the moving part under test. This gives:

$$Q_j = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} h_j \mid v_j(t) \mid dt \tag{9}$$

Thus, ignoring contributions of other kinds, usually of little importance in the case of nuclear reactors, and also referring to the case of a single control rod, the functional to be minimized is given in full by:

$$Q = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} \left(K_1\left(P(t) - P_o\right)^2 + K_2\left(T(t) - T_o\right)^2 + K_3|v(t)|\right)dt \tag{10}$$

The calculation of this functional requires a knowledge of the quantities $P(t)$, $T(t)$ and $v(t)$, which can be obtained by solving the system of equations relating to the reactor and the control system. These equations can be obtained by analysis of the dynamic behaviour of the reactor and synthesis of a control system satisfying the specifications of transient operation.

Considering now the problem of steady-state operation, dead zones of generic parameters are introduced into the feedback chains. The resulting system of equations thus leads to solutions $P(t)$ and $T(t)$, depending on the above parameters; in the same way, the velocity

$v(t)$ of each rod is related to the relative reactivity ΔK_b by the equation:

$$v(t) = \frac{d\Delta K_b}{dt}$$

The perturbation term in the described system of equations consists of signals which can be represented as reactivity perturbations. In the case of zero power reactors many studies (Refs 1, 2, and 3) have shown the possibility of drawing up a general scheme of these perturbations while, in power reactors, they are peculiar to each reactor (Refs. 4 and 5) and it is thus necessary to make experimental determinations from case to case.

An algebraic solution of the above system of equations is practically impossible by a direct route, but an analog method is feasible. Following this method the simulation of the perturbing signals and of the functionals are tackled in turn, while for the dynamics of the system reference is had to the relevant literature (Refs. 6 and 7).

The experimental approach followed for the simulation of the perturbation signals may be used for any kind of reactor, provided the perturbation in question is Gaussian and its spectral curve is known. An analysis of the neutron noise signal at the output of the ionization chamber, with a non-controlled reactor, gives the diagram of the spectral power density $\Psi_{ii}(\omega)$ (Refs. 4, 8 and 9) and, by measurements of the probability density, allows to detect if it has a Gaussian nature or not (Ref. 9).

The power spectral density $\Psi_{\rho\rho}(\omega)$ of the equivalent input noise signal, in reactivity, is obtained on the basis of the equation (Ref. 4):

$$\sqrt{\Psi_{\rho\rho}(\omega)} = \frac{\sqrt{\Psi_{ii}(\omega)}}{|G(j\omega)|} \cdot \frac{1}{I_o} \tag{11}$$

where $G(j\omega)$ represents the reactor transfer function, which therefore must be known, and I_o the mean value of the detector output current.

The analytic expression of the spectrum of r.m.s. amplitude of the output signal of the ionization chamber can be obtained by the method of the approximating meromorphic function applied to the logarithmic diagram of the modulus of $\Psi_{ii}^{\frac{1}{2}}(\omega)$ (Ref. 10).

Then, if equation (11) is applied, the spectral density of the r.m.s. value of the equivalent input noise is represented by a rational fraction of the type:

$$\Psi_{\rho\rho}^{\frac{1}{2}}(\omega) = \frac{K(1+j\omega\tau_o)\,(1+j\omega\tau_1)\ldots\ldots\ldots}{(j\omega)^n\,(1+j\omega\tau'_o)\,(1+j\omega\tau'_1)\,\ldots\ldots\ldots} \tag{12}$$

This expression takes account of the detector background noise, which is due to the statistics of the capture process in it, and, moreover, is usually suitable for a purely theoretical representation, for its contribution to $\Psi_{ii}(\omega)$ has a constant spectral density Ψ_{rr} and its value is related to the direct component I_o of the ionization chamber output current, by the equation (Ref. 4).

$$\frac{\Psi_{rr}}{I_o^2} = \frac{2q}{I_o} = \frac{K'}{P_o} \quad \text{sec} \tag{13}$$

where P_o is the power of the reactor in W, and q the charge released in the detector for each capture, so that K' represents a function of the position of the detector in the reactor.

The experimental data for the ratio Ψ_{rr}/ I_o^2 at a certain power P_o can be used to find the value of the constant K'.

This last-mentioned noise is Gaussian (Ref. 11), while the perturbation noise of the reactor itself may sometimes behave differently. In these cases the method of simulation described is inadequate, and it is necessary to record the noise directly on the non-regulated reactor and to introduce it into the analog computer.

In steady-state operation the system thus simulated supplies the signals P(t), T(t) and v(t) required for determining the partial functionals Q_1, Q_2 and Q_3. Integration over a finite time t_o of the square of the power and temperature variations and the modulus of the velocity is a way of determining the required functionals, although affected by a statistical error.

This error depends on the time t_o and the spectral shape of the perturbation. In order to choose a suitable analysis time t_o it should be noted that (Ref.12):

$$t_o = \frac{H}{\epsilon \,.\, \Delta f} \tag{14}$$

where ϵ represents the fractional error, Δf is a frequency band related to the perturbations, and H is a suitable constant dependent on the system.

The diagrams in figs. 1 and 2 show the analog circuits used for determining the value of functionals. The voltmeter M is read at the end of the measuring time t_o.

In conclusion, it may be noted that the procedure adopted for the optimization does not imply the linearity of the system nor any limitations on the character of the non-linearities introduced, which may be of any type provided are parametrizable. This makes it possible to transform the functional Q into an ordinary function, thus allowing the approach considered, inasmuch as the terms Q_1, Q_2 and Q_3 are obtainable for points as a function of the parameters of the non-linearities introduced, and a minimum condition is thus easily identifiable.

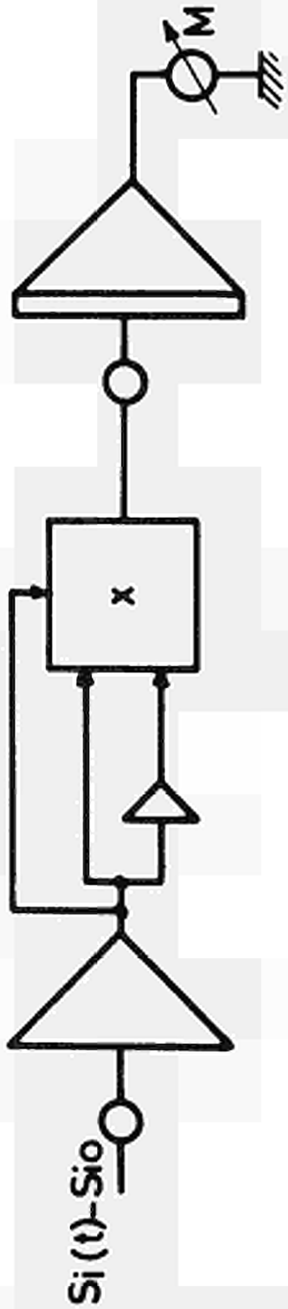

Fig 1

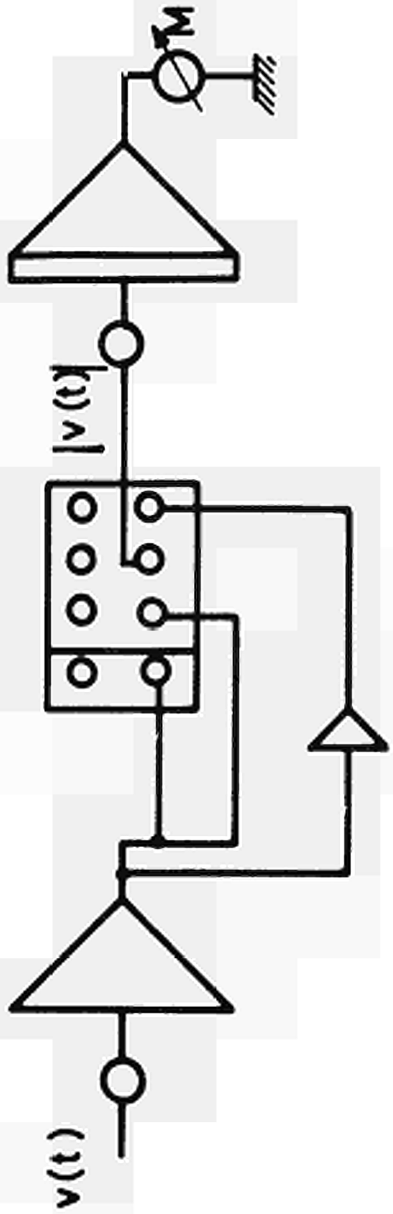

Fig 2

Fig. 1 : Diagram of the analog circuit used to evaluate the average square value of $(S_i(t)-S_{io})$.

Fig. 2 : Diagram of the analog circuit used to evaluate the average value of h. | v(t) |.

3) APPLICATION TO THE ISPRA-1 REACTOR

The parameters used in the simulation of the ISPRA I reactor and its control sistem were deduced from data obtained directly on the installation (Ref.9), together with some data from the available literature (Refs. 13 and 14).

The system of differential equations used for the simulations is as follows:

$$\frac{dP}{dt} = \frac{P}{\tau}(\Delta K - \beta) + \bar{\lambda} C$$

$$\frac{dC}{dt} = \frac{P}{\tau}\beta - \bar{\lambda} C$$

$$\Delta K = \Delta K_d + \Delta K_b + \Delta K_t$$

$$\frac{d}{dt}\Delta K_t = - \frac{1}{1800 \cdot P_o} P + \frac{1}{5}\Delta K_t \qquad (15)$$

$$v(t) = \frac{d}{dt}\Delta K_b$$

$$\frac{d\Delta K_b}{dt} = -6.6\frac{d^2}{dt^2}\Delta K_b - 11.65\frac{d^3}{dt^3}\Delta K_b - 5.1\frac{d^4}{dt^4}\Delta K_b - 0.4\frac{d^5}{dt^5}\Delta K_b +$$

$$- 4.4 \cdot 10^{-5}\Big[\frac{60}{P}\frac{dP}{dt} + \frac{240}{P}\frac{d^2P}{dt^2} - 500\frac{P_o-P}{P_o} - 6{,}250\frac{d}{dt}\left(\frac{P_o-P}{P_o}\right) +$$

$$- 13{,}000\frac{d^2}{dt^2}\left(\frac{P_o-P}{P_o}\right) - 5{,}000\frac{d^3}{dt^3}\left(\frac{P_o-P}{P_o}\right)\Big]$$

$$Q = \frac{1}{t_o} \int_o^{t_o} (K_1 (P(t) - P_o)^2 + K_2 (T(t) - T_o)^2 + K_3 . |v(t)|)\, dt$$

where the reactor is represented by the non-linearized equation of the neutron kinetics with a single group of delayed neutrons and taking into account an overall temperature effect ΔK_t.

In the third equation of (15), ΔK_d and ΔK_b represent respectively the reactivity introduced by the perturbations and the reactivity due to the feedback chain, i.e., the control rod. Lastly, P_o is the value of the power set up, i.e. the reference of the control chain, and T_o is the equilibrium temperature of the reactor at the power P_o.

Fig.3 shows the block diagram of the system under consideration. The perturbation signal is broken down into two parts, namely, the noise of the reactor itself and the background noise of the ionization chamber. The former is obtained by the methods already described and on the basis of the available data (Ref.9). It is of the following type:

$$\Psi_{\rho\rho}^{\frac{1}{2}}(\omega) = \frac{K}{(1+j\omega\tau_1)\,(1+j\omega\tau_2)^2} \qquad (16)$$

where the double pole with real time-constant τ_2 in effect replaces for the sake of simplicity two complex and conjugate poles; since these latter have however a damping coefficient very close to unity, the approximation may be considered valid.

The time constants τ_1 and τ_2 have values of about 3.2 and 0.23 sec respectively.

The value in reactivity of K, deduced from (11) with the data already in our possession (Ref.9), is about 18 pcm.

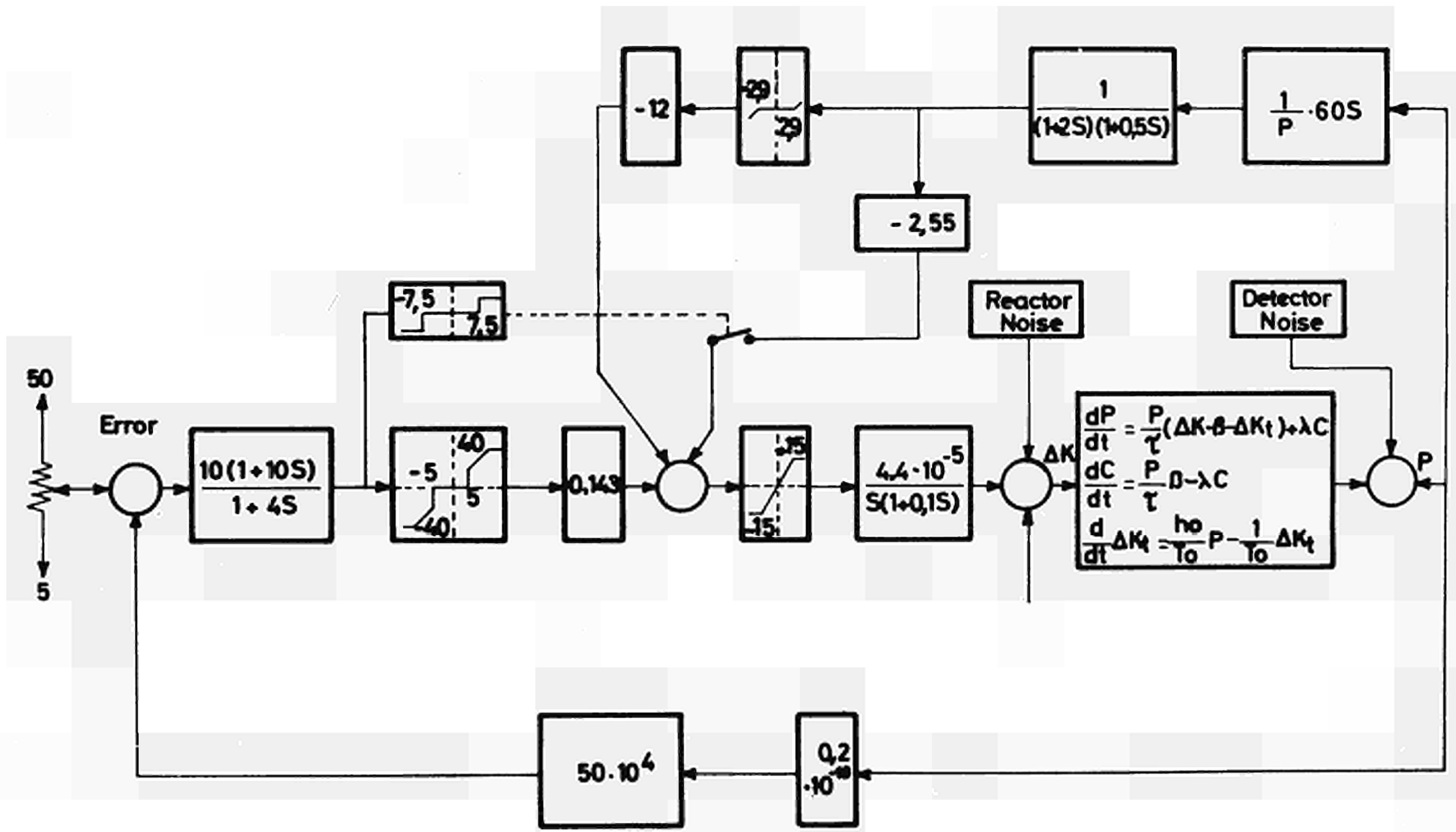

Fig. 3 : Block diagram of the control system of the Ispra - 1 reactor.

On the other hand, in relation to the white background noise of the ionization chamber, the value of K' in (13) may be assumed to be about $2.3 \cdot 10^{-2}$ $Wsec^{\frac{1}{2}}$, as the value of Ψ_{rr}/I_o^2 at 5MW is about 10^{-10} sec (Ref.9).

The regulation diagram in fig.3 shows the separate action of a proportional effect reaction chain and of another of derivative type. In view of their different influence on the noise, it is logical to introduce separate dead zones into the two circuits.

The results of the evaluations of the partial functional Q_1, Q_2 and Q_3, carried out by the analog techniques already described, are given in the diagrams in figs. 4-9 . Figs. 4-6 show the trends of Q_1, Q_2 and Q_3 as functions of the dead zone of the proportional chain (or error dead zone), while the dead zone in the derivative channel (period dead zone) has been assumed as a parameter. In addition, in order to visualize more clearly the behaviour of the two-dimensional functions, the same quantities are shown in figs. 7-9 as functions of the period dead zone, the error dead zone being taken in its turn as a parameter.

The minimization is effected by combining the three partial functionals with the appropriate constants K_i according to what is shown by the last equation in system (15). These constants, the choice of which is related to considerations on the relative importance of the various partial functionals, define the functional Q apart from a multiplicative constant γ . A suitable criterion for the determination of this constant derives from the physical consideration that there is a total functional independent of the constants K_i/γ for equal partial functionals. It follows that the choice of K_i is bound up with the condition:

$$\frac{1}{\gamma}(K_1 + K_2 + \ldots\ldots\ldots\ldots + K_n) = \text{cost.}$$

In the case of the reactor under consideration K_2 is practically zero, since such reactor was intended for irradiation experi-

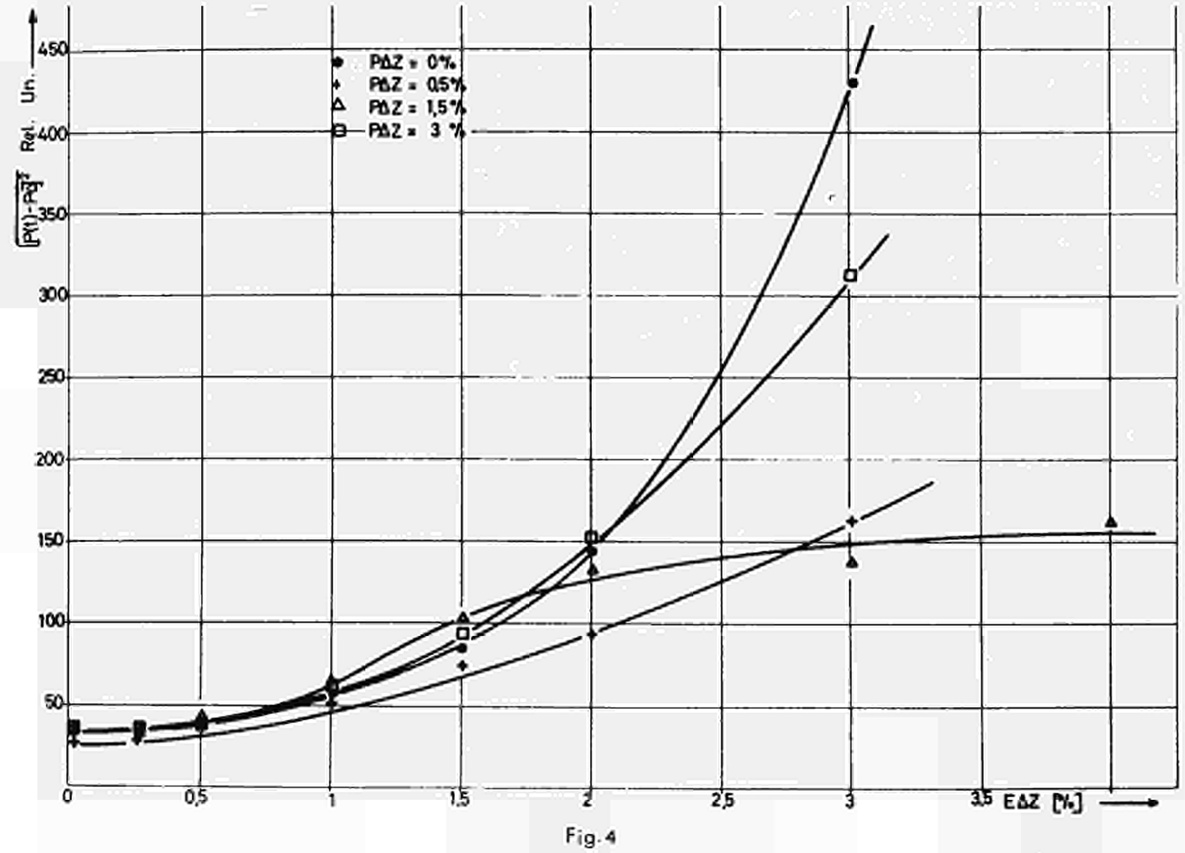

Fig. 4

ig. 4 : Curve for the average square of the power variations of Ispra 1 as a function of the error dead zone.
EΔZ = error dead zone - PΔZ = period dead zone.

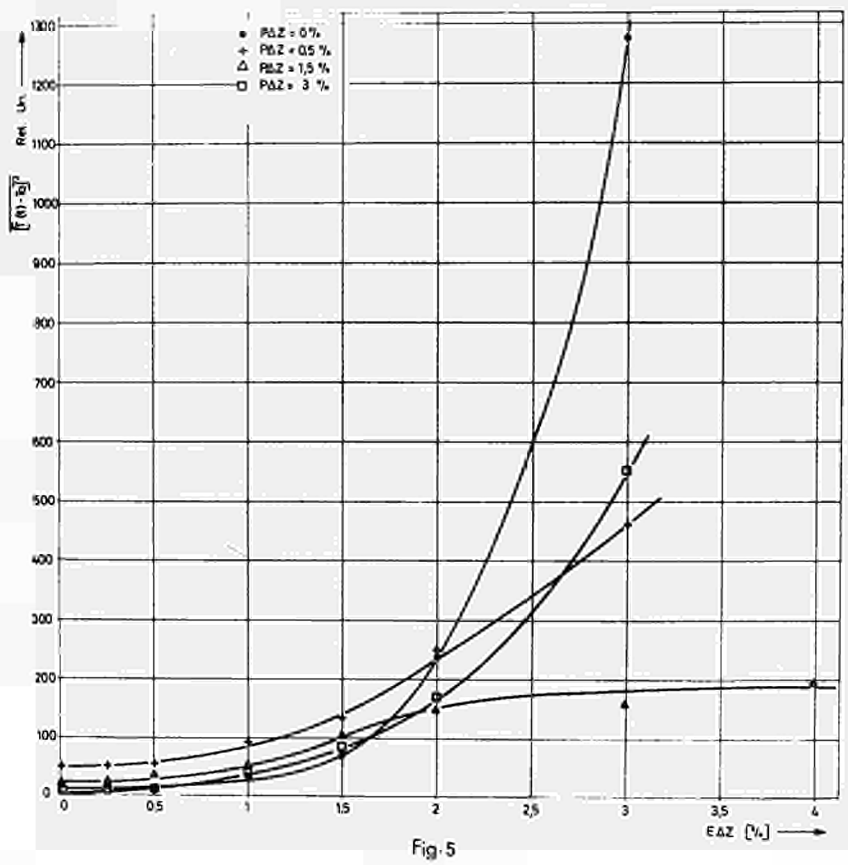

Fig. 5

Fig. 5 : Curve for the average square value of the temperature variations of Ispra - 1 as a function of the error dead zone.

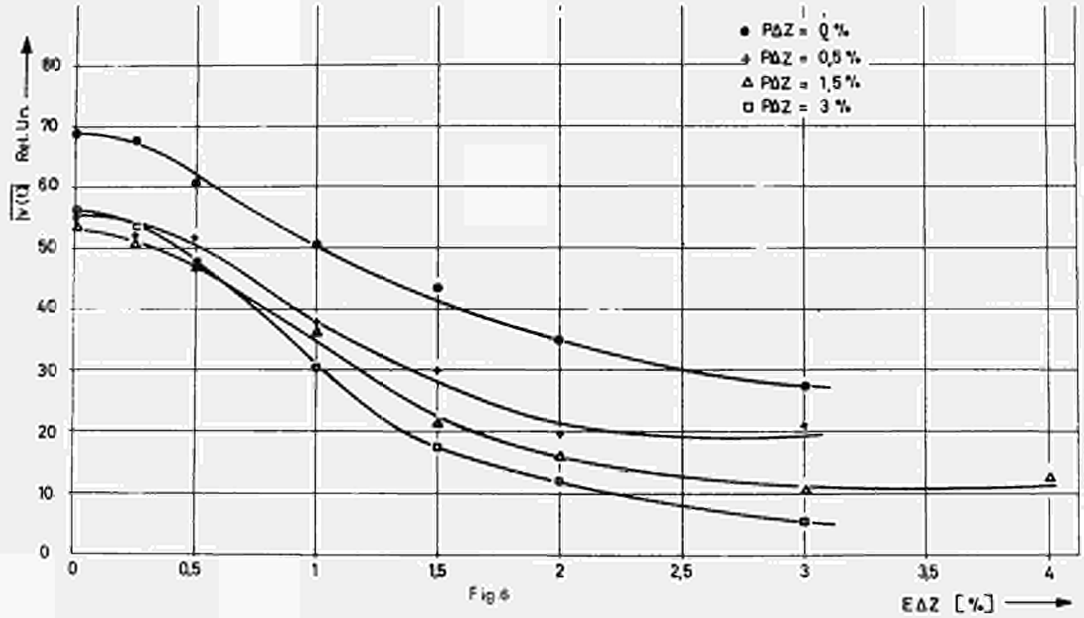

Fig. 6 : Curve for the average modulus of the velocity of the control rod of Ispra-1 as a function of the error dead zone.

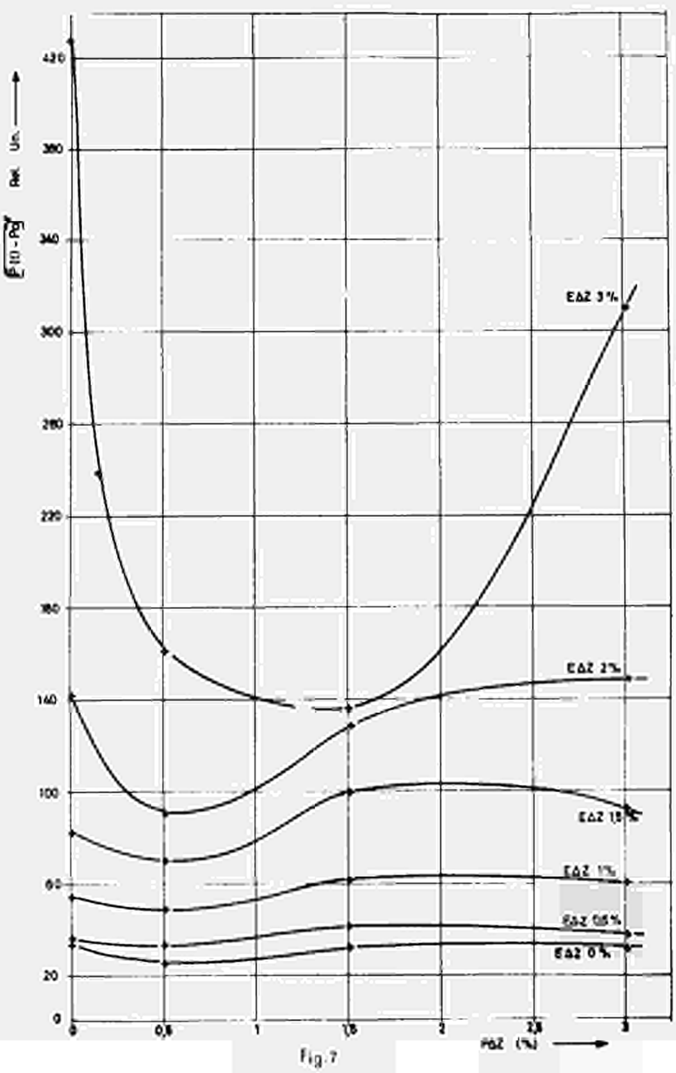

Fig. 7 : Curve for the average square value of the power variations of Ispra-1 as a function of the period dead zone.

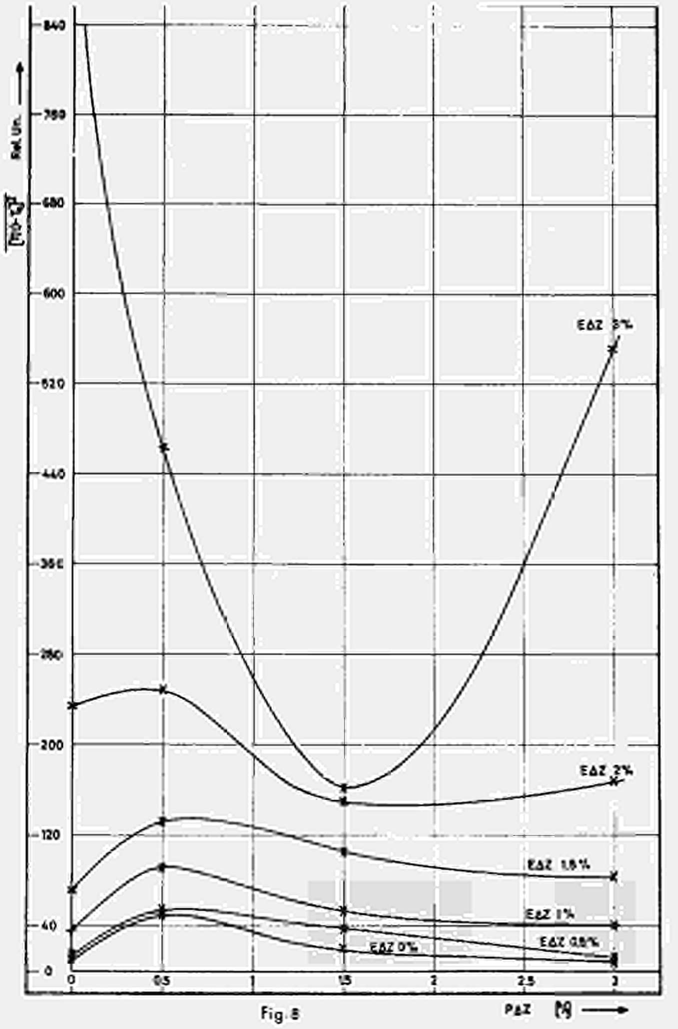

Fig. 8 : Curve for the average square value of the temperature variations in Ispra-1 as a function of the period dead zone.

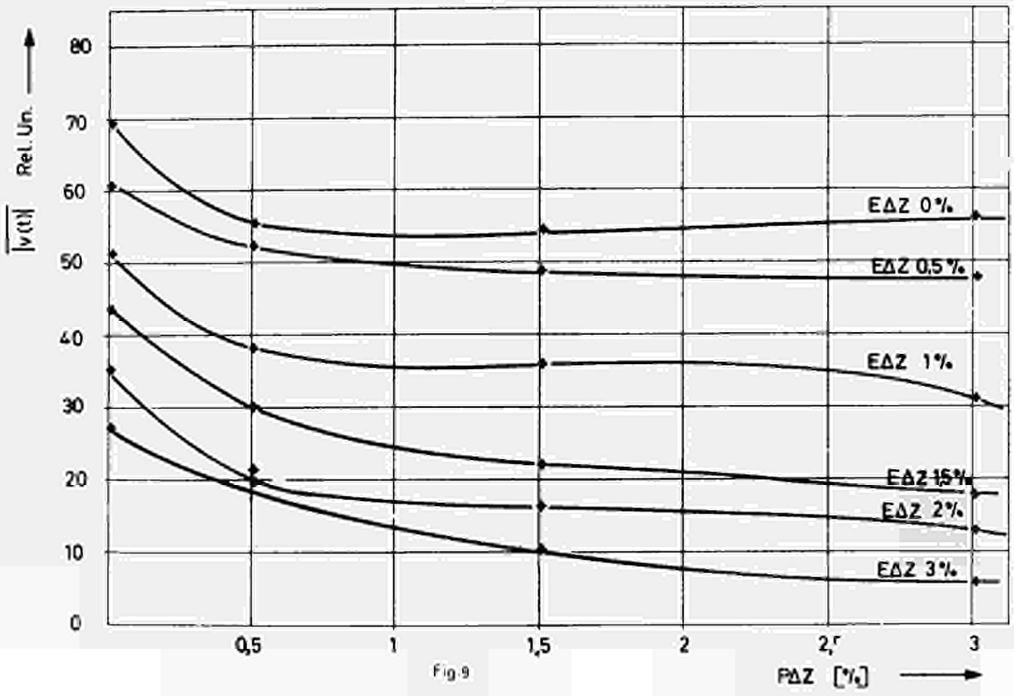

Fig. 9 : Curve for the average modulus of the velocity of the control rod of Ispra-1 as a function of the period dead zone

ments at low temperature (about 70°C in the moderator). Therefore the temperature related phenomena are not relevant. The values given to K_1 and K_3 are respectively 0.4 and 1. Taking into account the scale factors, this amplies that the same relative weight is attributed to both a stationary r.m.s. error of 0.5% and a control rod mean speed of about 1 p.c.m./sec (= 2,5 mm/sec).
At the speed mentioned above, the wear and tear phenomena on the road supports require the supports to be replaced after about five years of work.
It is not essential for the moment to choose γ.

The curves in fig.10 were calculated by introducing the values of these constants. They show the total functional Q as a function of the period dead zone with the error dead zone equal to 0,0.25, 0.5, 1, 2, and 3%. The graphic analysis also conducted with the help of the reciprocal curves in fig.11 leads to the determination of the minimum of the functional Q for the values of 1% and 1,5% of the error dead zone and the period dead zone respectively.

It should be noted that while the choice of the error dead zone is univocal, the period dead zone includes a relative minimum so that the choice of the value 1.5% is based on a compromise between minimum conditions and safety conditions, the latter leading to the exclusion of excessively large dead zones.

This result having been obtained, it is usefull, in order to verify the permanence of the minimum conditions in time, to determine the behaviour of the functional Q in relation to variations in the amount of the perturbations, their spectral curve being assumed to be unchanged. The partial functionals Q_1, Q_2 and Q_3 are therefore found by using the analog technique described, fixing the two dead zones, however, at the values just found but varying the amplitude of the reactor's inherent noise.

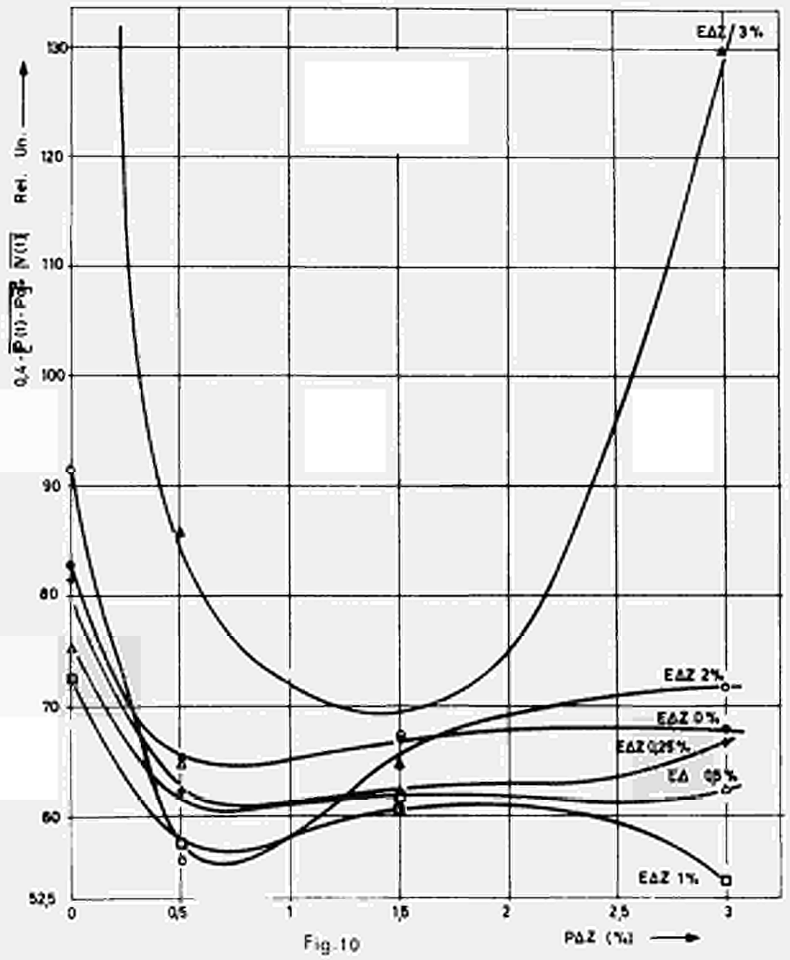

Fig.10 : Curve for the functional $0.4\cdot\overline{(P(t) - P_o)^2} + \overline{|v(t)|}$ as a function of the period dead zone.

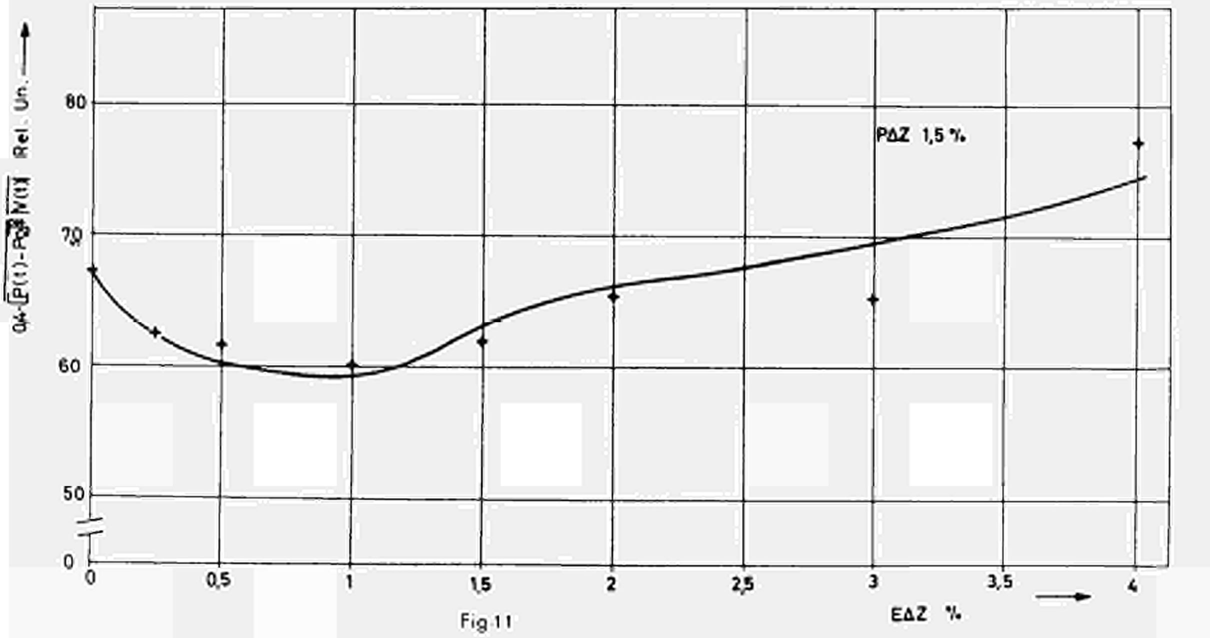

Fig. 11 : Curve for the functional $0.4\cdot\overline{(P(t) - P_o)^2} + \overline{|v(t)|}$ as a function of the error dead zone.

Fig.12 shows the points thus obtained, as a function of the ratio between the amplitude of noise introduced and that of the nominal noise. Similarly fig.13 shows the curve for the total functional Q, evaluated by using the values of the constants K_i already given; the existence of a minimum near the nominal noise value ensures permanent satisfactory working conditions.

For the sake of illustration, finally, the diagrams in fig.14 are given, which show, for three different values of the error dead zone, the shape of the power-error signal, the position and velocity signal of the control rod, the control signal of the rod drive mechanism, the period, the part of the drive mechanism control signal due to the period channel alone, the perturbation signal corresponding to the reactor noise, and, lastly, the temperature fluctuations $T(t)-T_o$.

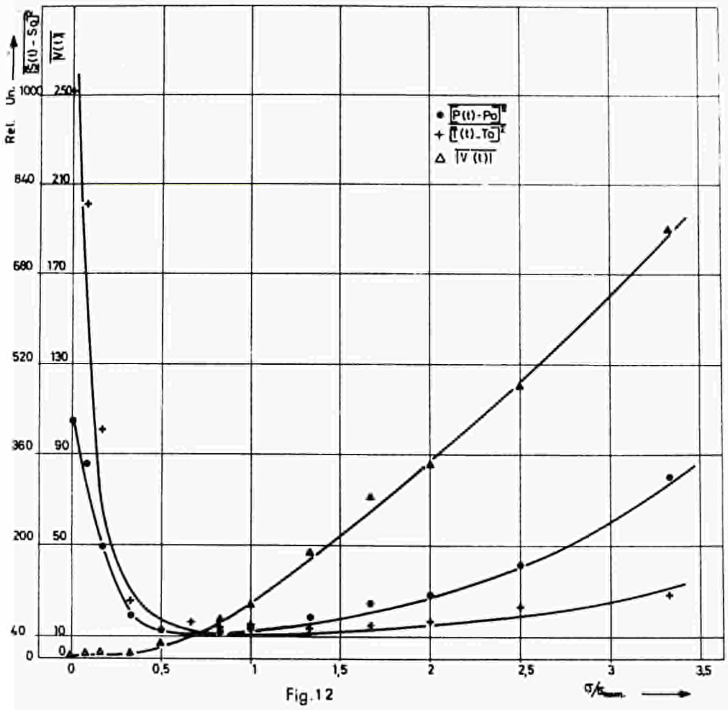

Fig. 12 : Curve for the average square values of the power and temperature variations, and of the average modulus of the velocity of the control rod of Ispra-1 as a function of the r.m.s. amplitude of the perturbation signal.

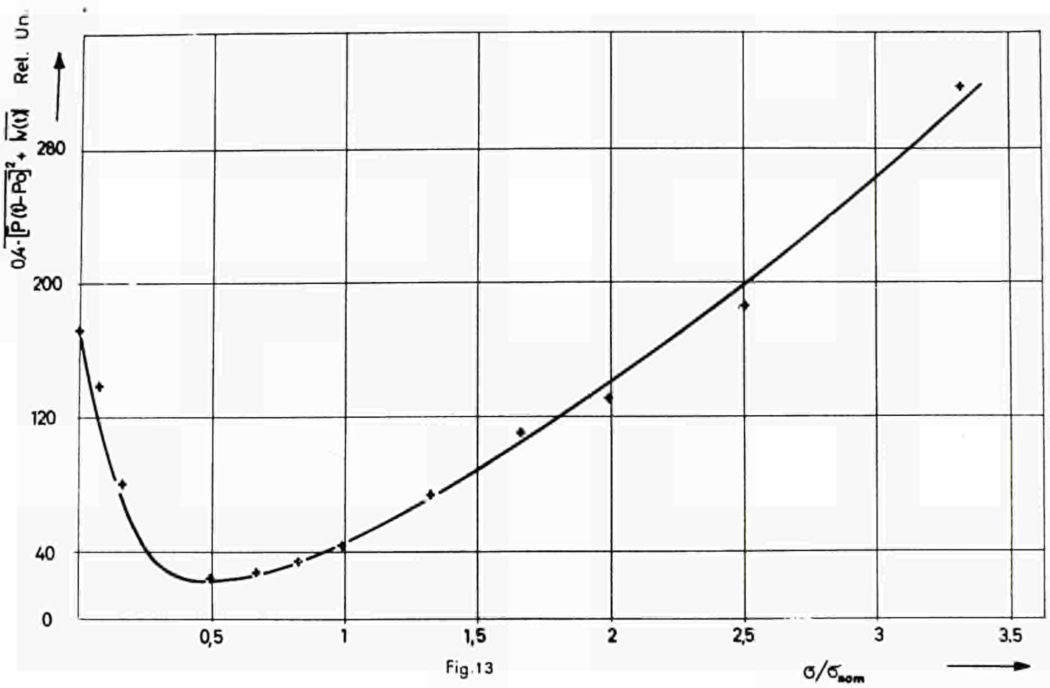

Fig. 13 : Curve for the functional $0.4 \cdot \overline{(P(t) - P_o)^2} + \overline{|v(t)|}$ as a function of the r.m.s. amplitude of the perturbation signal.

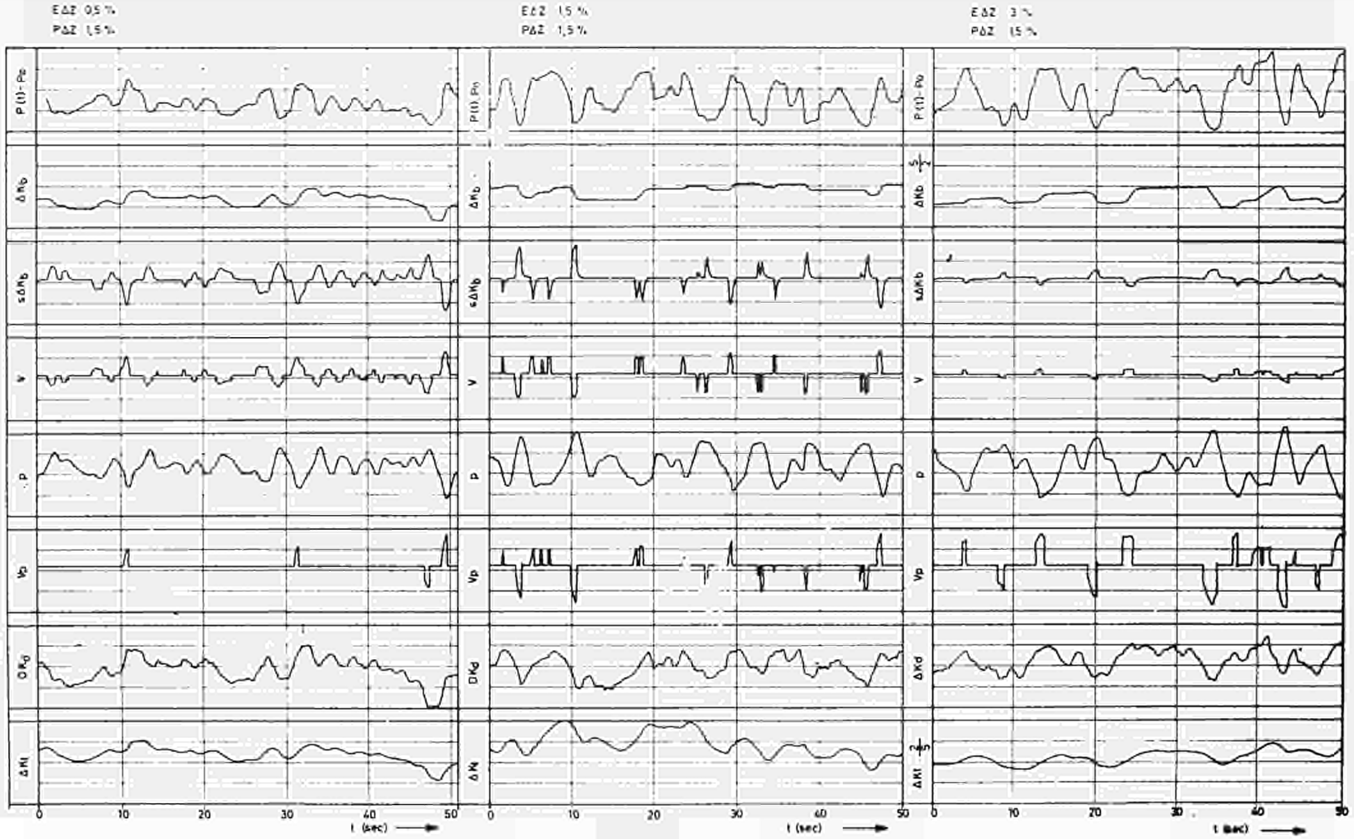

Fig.14

Fig. 14 : Curve for some variables of the control system of Ispra-1 in steady-state conditions at 5 MW with nominal period dead zone (1.5%) and error dead zone equal to 0.5, 1.5 and 3%.

$P(t) - P_o$ = power error signal; ΔK_b = signal of control rod position; $s\Delta K_b$ = velocity of control rod; V = control signal of the rod drive mechanism; p = period signal; V_p = part of the control signal of the rod drive mechanism due to the period channel; ΔK_d = perturbation due to the reactor noise; ΔK_t = $T(t) - T_o$, variation of the temperature reaction.

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Alfred Nobel

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