5.5. DIGITAL REACTIVITY METER, M. Copic, B. Valantic (Ljubljana, Yugoslavia)

Digital reactivity meters (DRM) are comming into more general use lately, either as separate instruments with built-in micro-computers or implemented on the special purpose process computers. Their superiority over the older analog reactivity meters lies not so much in the improved accuracy as in their versatility. Their full potential is certainly not realized yet in practice of reactor instrumentation and control DRM's are, up to now, mostly used as measuring instruments, e.g. for calibration of control rods, and there are only a few cases of their incorporation into the control systems of the reactors. To move in this direction there is more development work needed. First of all, fast algorithms are needed for inverse kinetics equations to relieve the computer for more important tasks of reactor model solving in real time. The next problem is the incorporation of the reactor thermal-hydraulic model into the DRM so that it can be used in the power range. Such an extension of DRM allows presentation not only of the instantaneous reactivity of the system, but also the inserted reactivity can be estimated from the temperature reactivity feed-backs. One of the applications of this concept is the anomalous digital reactivity monitor (ADRM) as part of the reactor protection system.

As a solution of the first problem, a fast algorithm for solving the inverse kinetics equations has been implemented in the off-line program RODCAL on CDC 1700 computer and tested for its accuracy by performing different control rod calibrations on the reactor TRIGA at our Reactor Center [1,2]. The fast algorithm is based on two main concepts: the low sampling rate of the neutron flux and the use of the integral form of the inverse kinetics equation. By a low sampling rate we mean one or only a few samples per second at most. Certainly the sampling rate has to be adjusted to the rate of the reactivity change but, as we will show later, even for rod drop measurements the sampling rate of 5 samples per second is acceptable to determine the reactivity worth of the control rods in the range up to 5 dolars of antireactivity. Such a low sampling rate combined with the integration of the inverse kinetics equation over the same time intervals requires very small computational effort. But to achieve the required accuracy by the integration over such rather long time intervals, one has to use the integral form of the inverse kinetics equation. Hence, our fast algorithm is based on the discretization of the starting equation for the reactivity ρ, measured in dolars,

$$\rho n = n\,(k-1)/(\beta k) = \Lambda \dot{n}/(\beta k) + \int^{t} dt\, H(t-t')\, \dot{n}(t') \qquad (1)$$

where the kernel of the Voltera type integral equation is given by

$$H(t) = \sum_{j=1}^{6} a_j \exp(-\lambda_j t) \qquad (2)$$

with a_j the relative yeilds and λ_j the time constants of the delayed neutron precursors.

To obtain the finite time series approximation of Eq.(1), the recursion formulas are used for the contributions of the

delayed neutrons. To evaluate the integrals, a linear interpolation between two sucsessive value of $\dot{n}(t_i)$ has been used. For fixed time intervals $t_i - t_{i-1} = \Delta$ the coefficients of the recursion formulae are precomputed according to[3]

$$\begin{aligned} U(x) &= \exp(-x) \\ V(x) &= (1 - (1+x)\, U(x))/x^2 \\ W(x) &= (U(x) - 1 + x)/x^2 \end{aligned} \tag{3}$$

so that at each time step the contributions of the delayed neutrons are updated according to

$$Q_{ji} = U(\lambda_j \Delta)\, Q_{ji-1} + V(\lambda_j \Delta) \Delta \dot{n}_{i-1} + W(\lambda_j \Delta) \Delta \dot{n}_i \tag{4}$$

The reactivity is then calculated from the ratio

$$\rho_i = (\Lambda \dot{n}_i / \beta + \sum_{j=1}^{6} a_j\, Q_{ji}) / n_i \tag{5}$$

The initial conditions are set at the steady state when the reactivity is zero, so that all Q_{jo} are zero also.

The relative error due to the time discretization is estimated to be

$$|\delta\rho|/|\rho| = 0{,}083\ (\omega \Delta)^2 + \ldots \tag{6}$$

where ω is either the time constant for exponential time variations or the circular frequency for a periodic process. For the periodic process the relative error is estimated as the ratio of the amplitudes. For the cases investigated, the phase shift is negligible.

To reduce the noise contributions some smoothing of the raw data is performed in two steps. The basic sampling rate at the data collection stage is 10 samples per second with the subsequent addition of m samples, $2 \leq m \leq 30$, performed by an on-line data acquisition program on the CDC 1700 computer. The program RODCAL subtracts the estimated background, caused by the incomplete compensation of the linear power channel, from the input data and then further smooths the data by a five point digital filter, evaluationg at the same time n_i and $\dot{n}_i$ using symmetric, center point formulae.

The program RODCAL has been tested by three types of control rod reactivity measurements:

(i) "drive in" measurements of the integral and the differential reactivity worths,
(ii) "rod drop" measurements of the integral worths,
(iii) "periodic" measurements of differential reactivity worths and the evaluation of the relative errors of RODCAL.

The negative reactivities of the control rods as determined by the RODCAL using 1 sec sampling intervals on the "drive in" neutron flux traces are presented on Fig. 1 and Fig. 2. The coincidence of the reactivities as determined by the RODCAL and by the assimptotic time period measurements for the regulating rod, Fig. 1, is almost perfect over most of the curve. The TRIGA reactivity tables, supplied by General Atomic, are calculated by the same set of basic data, a_j and λ_j, as used in the RODCAL[4], so that any difference between the results is caused either by the error generated in the RODCAL, estimated to be in this particular case arround 0,5 % at 1 $, or by the accumulation of the measuring errors in the assimptotic period method, totaling 1,5 % at 1 $. Hence, we cannot speak about the calibration of the DRM, because its accuracy is better than the standard method, e.g. the assimptotic period measurements.

The range of the negative reactivities, measurable by RODCAL, is demonstrated on Fig. 2, where the calibration curves obtained by the "drive in" method, are presented for the shim and the safety rods. The combined curve for the simultaneous "drive in" of the safety and the regulating rods is shown also. In this way the negative reactivity of 5 $, with the accuracy of better than 4 % is determined.

It is interesting that the integral worths of the control rods are obtained by the "rod drop" with a better precission than by the "drive in" method, particularly for large negative reactivities, of the order of 4 $. Inspite of the large local error during the time of the drop, caused by the relatively large sampling interval of 0,2 sec and by the effective RC constant of the measuring channel (estimated to be arround 0,35 sec), the integral reactivity worths have errors arround 2 % only. The main reason for better accuracy lies in the smaller decrease of the neutron flux immediately after the end of the drop relative to its initial steady value before the drop as compared to the decrease during the "drive in" process which takes more than 90 sec by our control rod drives. Namely, due to the appreciable time constants in our measuring channel, we cannot switch the power ranges during the data accumulation time. Thus, at large decreases of the neutron flux level, the loss of accuracy is caused by the A/D conversion due to the final word length.

Therefore, it is not surprising that the best precission is obtained by the "periodic" measurements (really semiperiodic) of the finite segments of the control rods. Fig. 3 shows traces of the calculated reactivity and the variations of the neutron flux as generated by the trapezoidal movement of the regulating rod with an approximate period of 90 sec. The reactivity has been evaluated from the same neutron flux trace by RODCAL, using different time intervals from 0,5 sec up to 3,0 sec. Inspite of an appreciable higher harmonics content the average relative

error as a function of the time interval Δ agrees prety well with the estimate, Eq. (6). On the other hand, the maximum local error, appearing always at the corners of the reactivity trace, is for an order of magnitude larger, but remains less than 1 ¢ even for the time interval of 3 sec. It should be noted that on the segments of constant reactivity, the standard deviation is almost independant of the time interval Δ and it is arround 0,02 ¢.

The sensitivity of the DRM is demonstrated by Fig. 4 where the differential reactivity curves, obtained by 0,5 sec sampling interval, are presented for the regulating rod. The fine undulating structure of the differential curve has been explained by dismantling the regulating rod, finding a broken and a displaced pin in its head. The maladjustment and the displaced pin caused the regulating rod to vibrate with the period of the holes in its guide tube from the moment the connecting rod entered the top of the guide tube. The repair of the connecting head and the adjustment of the regulating rod drive support removed the fine structure from its differential reactivity curve. To appreciate the sensitivity of our fast algorithm at low sampling rates, note the amplitude of the undulating fine structure and its reproducibility on Fig. 4. By this example, the usefulnes of the DRM as a diagnostic tool is well demonstrated.

To conclude, it can be stated on the bases of the accumulated experience, that we achieved the first goal by the program RODCAL. We have a sufficiently accurate fast algorithm, that can use slow sampling rates. The execution time of RODCAL on CDC 1700 computer requires 15 msec per time step and this is indeed short enough.

We intend to extend the applicability of DRM. We are now investigating the thermal-hydrodynamic model of the TRIGA reactor

with the aim of incorporating it into the multipurpose reactivity meter as mentioned at the beginning. Here the problem is attaining sufficient accuracy over as wide a range of reactor power as possible and at the same time keeping the model reasonably simple so that it can be implemented on the process computer to be run in real time.

References

(1) M.Čopič, Two Methods for Reactivity Measurement, Work Report, IJS-DP-1033, Dec.1976 (In Slovene).

(2) J.Špiler, Digital Reactivity Meter (Diploma Thesis), Faculty for Electronics, University of Ljubljana, March 1977 (In Slovene).

(3) H.P. Flatt, Reactor Kinetics Calculations in Computing Methods in Reactor Physics (edited by H.Greenspan, C.N. Kelber and D. Okrent), pp. 500-504, Gordon and Breach Science Publishers, New York (1968).

(4) G.R. Keepin, Physics of Nuclear Kinetics, Addison--Wesley, Reading (1965).

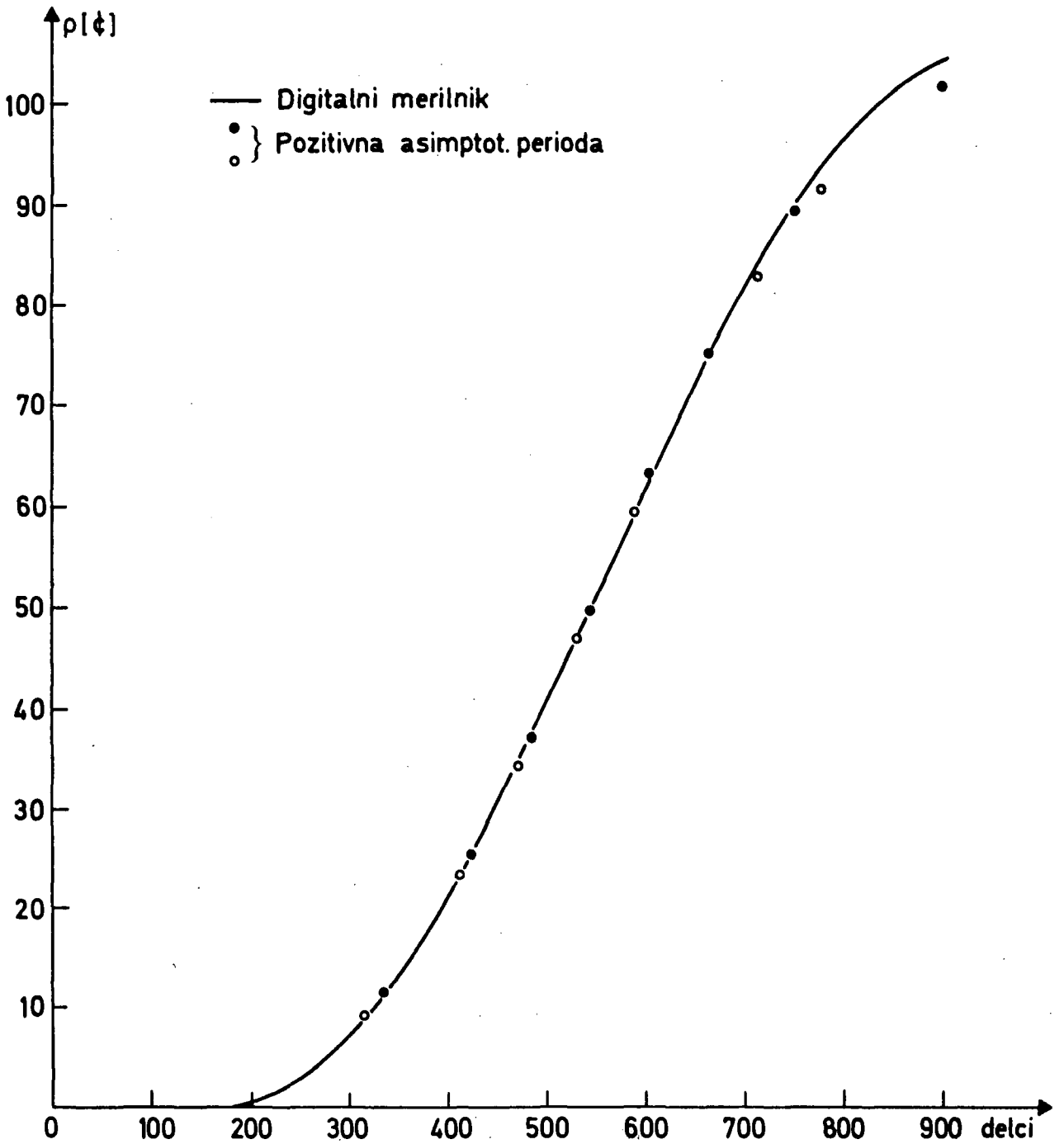

Fig. 1. Reactivity worth of the regulating rod. Comparison of the DRM results with the data obtained by the asymptotic period measurements.

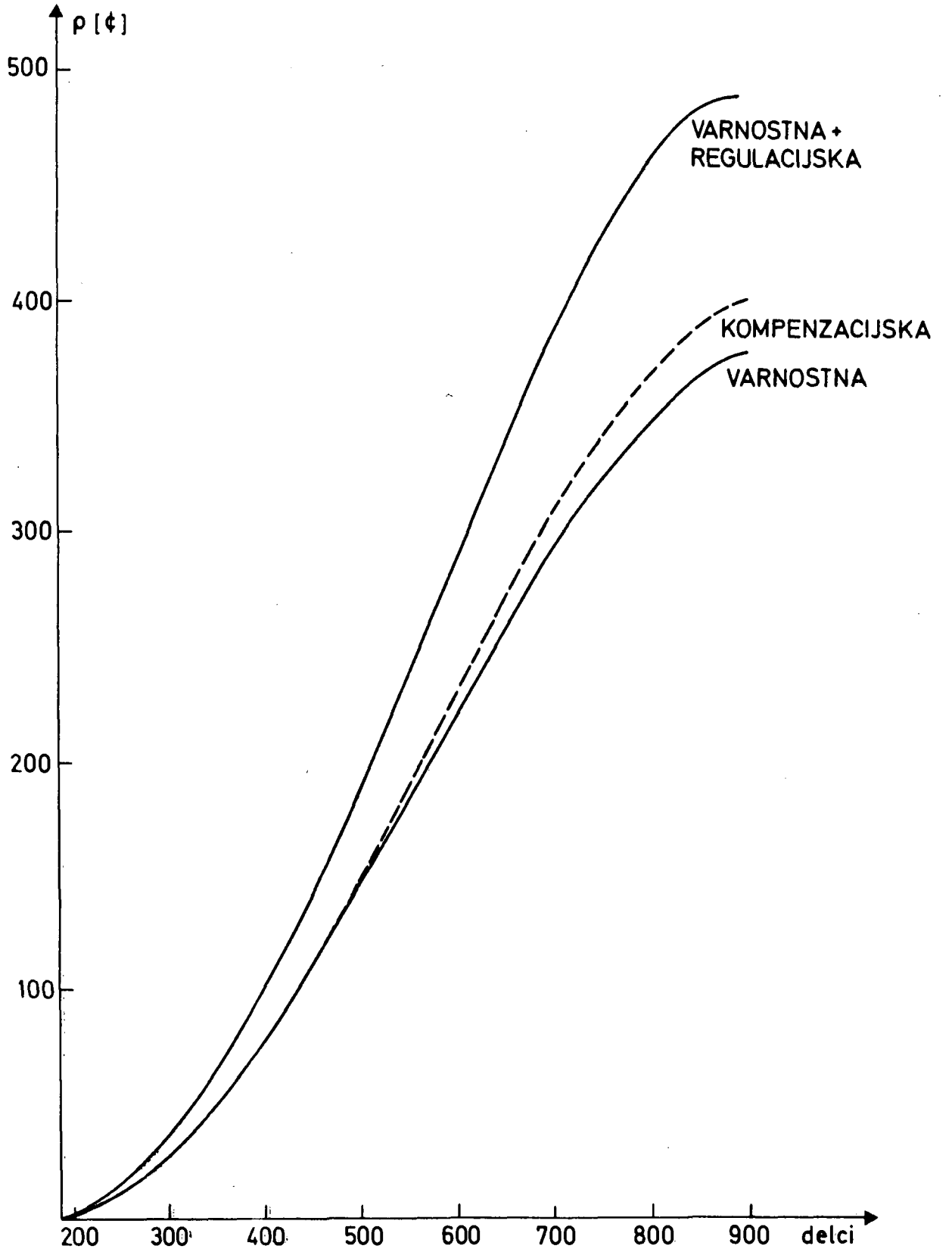

Fig. 2. Reactivity worths of the safety ("varnostna") and the shim ("kompenzacijska") rods.and the sum-curve of the safety and the regulating rods.

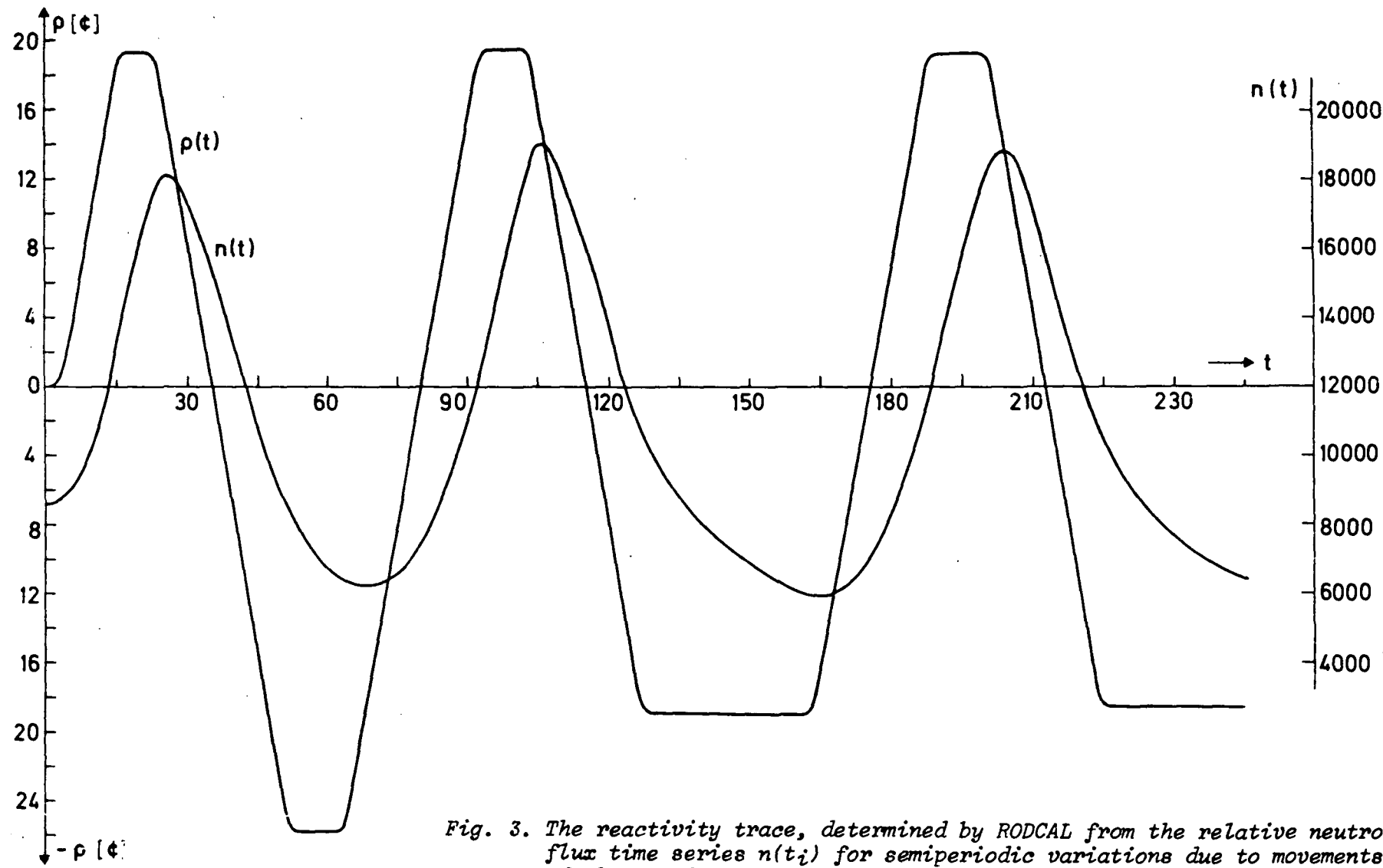

Fig. 3. The reactivity trace, determined by RODCAL from the relative neutron flux time series $n(t_i)$ for semiperiodic variations due to movements of the regulating rod.

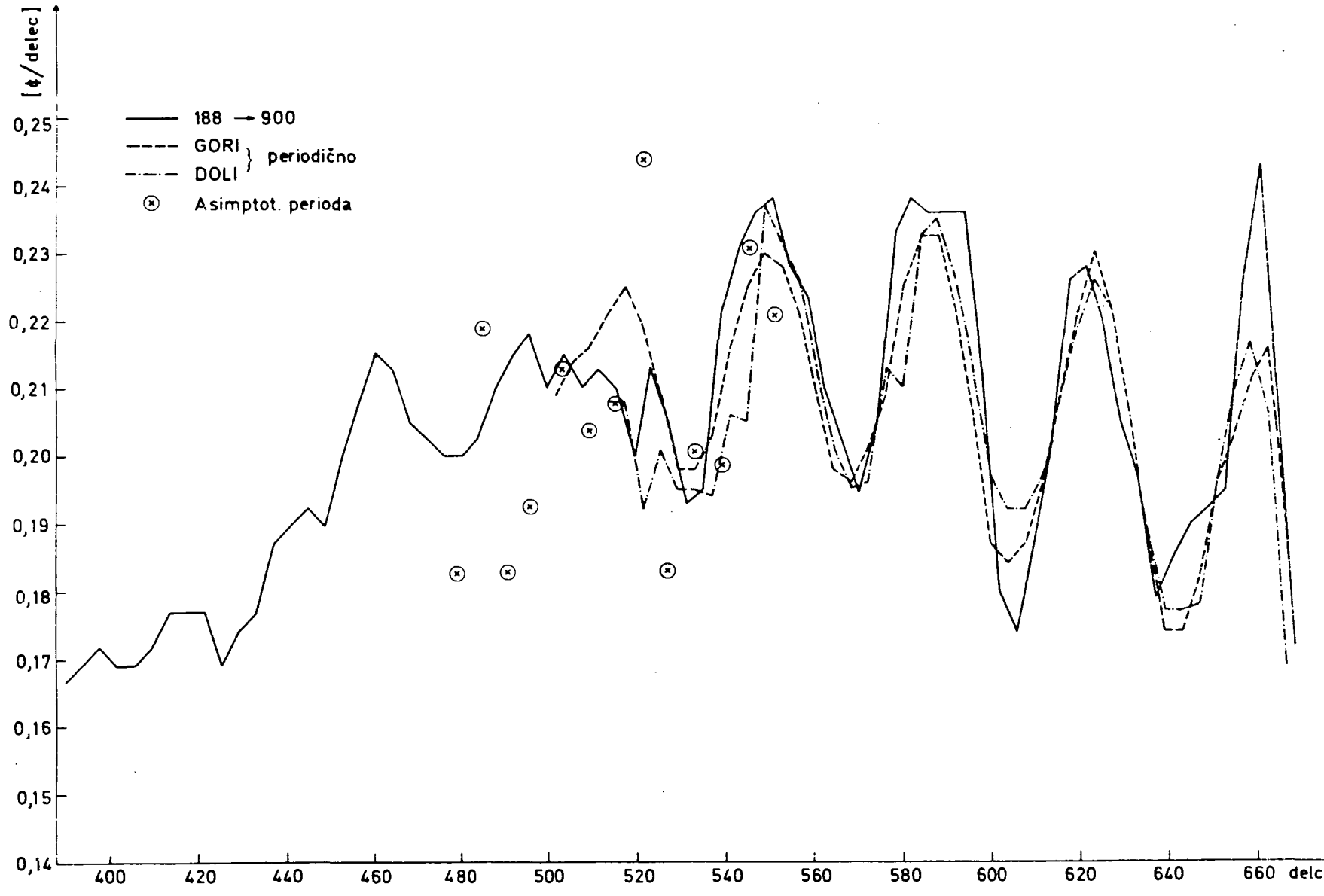

Fig. 4. The differential reactivity worth of the regulating rod before repairs of its connecting head.