SPND DETECTORS RESPONSE AT THE CONTROL ROD DROP IN VVER-1000. MEASUREMENT AND MODELLING RESULTS

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ABSTRACT

The paper analyses and discusses possibility of neutron flux inspection in the VVER core during fast dynamic processes applying existing in-core monitoring system.

The structure and functions of the system, basic principal of detector functioning and its temporal parameters are described briefly.

To assess the ability of such dynamic monitoring the event with control rod drop happened during operation of Kozloduy NPP Unit 5 is observed – at the level of power close to nominal one of the rod from control group shifted to the lowest position at ~2 seconds. In-core detectors readings at the process were registered and processed with mathematical methods that allow to single out only the prompt part of the signal. Results of the processing are presented.

Furthermore, the process observing have been modelled with 3D dynamic code NOSTRA. Results of modelling are presenting in a paper, and comparing with experimental ones. A good agreement achieved.

The analysis of measurements and its imitation give a hope that with an aggregate signal of detectors the measurement of control rod worth could be provided, and it allows to avoid of influence of spatial effects that are significant at standard technique with ex-core ion chambers.

1. SYSTEM BRIEF DESCRIPTION. TIME PERFORMANCE OF DETECTOR

In-core monitoring system (ISCM) of VVER-1000 is intended for the monitoring of the thermal power of the core, of the heat balance of the unit, and of power density field and it's functional (in a space of 163×16 points). Modernized systems installed on the Unit 3 of Kalinin NPP and on the Tianwan NPP, have also some new functions:

- Pin-by-pin calculation of the power density (in a space of 163×16×312 points) and determination of fuel pin points with the least margin in terms of linear heat rate and DNBR;

- Preventive protection signal forming for the control and protection system in case of violation of limits for local parameters with delay not more than 2 seconds.

The measurement of the power density in the VVER-1000 core is carried out by neutron detectors assemblies that are allocated in the central tube of FA or in special tube instead of one of fuel pin. Each of the assembly contains 7 β-emission neutron detectors, also called self power neutron detectors (SPND). Sensitive part of the detector is cylindrical emitter, manufactured from neutron-sensitive material of rhodium (Rh). Under the neutron irradiation in the body of rhodium emitter radioactive isotopes are forming, and during the decay they emit high-energy β-particles, that arise electric current in the circuit. The diagram of nuclear reactions in the rhodium emitter is presented on the Figure 1.

The detector current is a sum of activation part J_a, instantaneous part J_k, corresponds to the Comton's and photo-electrons, and part J_g related to the reactor γ-radiation influence. Design of the detectors allows avoiding background current of the connection lines. With a high accuracy, each of detector's sum current parts J_a, J_k, J_g is proportional to the neutron flux density in chosen position, but the most part, activation part, is forming with significant delay because of β-decay of Rh^{104m} and Rh^{104} (see Figure 1). To use detector readings for the monitoring of dynamic processes in the core it is necessary to eliminate the delay in it.

Mathematical model of current forming in the rhodium SPND under the neutron flux is a system of differential equations (1)

$$\begin{aligned}
\frac{\partial m_1(t)}{\partial t} &= a_1 n(t) - \lambda_1 m_1(t), \\
\frac{\partial m_2(t)}{\partial t} &= a_2 n(t) + \lambda_1 m_1(t) - \lambda_2 m_2(t), \\
i(t) &= cn(t) + \lambda_2 m_2(t),
\end{aligned} \tag{1}$$

where n(t) – neutron flux;

i(t) – resulting neutron flux;

λ_1 , λ_2 – β-decay constants for Rh^{104m} and Rh^{104} ($\lambda_1 = 0.0027\ s^{-1}$, $\lambda_2 = 0.0164\ s^{-1}$);

a_1, a_2 – constants, proportional to rhodium (Rh^{103}) absorption cross-section resulting formation of Rh^{104m} and Rh^{104} isotopes ($a_1 = 0.061$, $a_2 = 0.879$);

a_1+a_2 – activation part ($a_1+a_2=0.94$);

c – instantaneous part c=6%.

Delay elimination problem could be solved with multiplication of measured signal on the inverse matrix of transfer function of the SPND (so called corrective filter). In brief, the corrective filter technique is of following:

- Solving equations (1) by Laplace transformation method, the transfer function of SPND is defining, or (the same) defining the analogue filter (P_S);
- Analogue filter parameters conversing to the digital filter P_Z by bilinear transformation ($P_S \Rightarrow P_Z$);
- Parameters of the inverse digital filter P_Z^{-1} are calculating.

The digital corrective filter obtained as described can fully eliminate the delay, but it amplifies the noise. With the exact delay compensation (delay less than 0.1 second) for the standard SPND the noise of the signal is increasing in ~17 times [1].

Necessary combination of delay elimination effect, an accuracy and stability are distinguishing features of the Kalman filter, when it incorporates the elements of the SPND transfer function [1]. It allows optimising the level of dynamic error (delay) elimination and noise amplification by setting of some parameters. Kalman filter utilized in the ICMS of VVER-1000 guarantee the noise amplification coefficient less than six with the delay less than 0.5 second.

2. THE PURPOSE OF THE RESEARCH. PROBLEMS UNDER CONSIDERATION

The purpose of the research presented in the following paper is to confirm the ability of the existing ICSM to monitor fast dynamic processes in the VVER core. It is assumed to utilize the delay elimination algorithm based on Kalman filter for SPND signals. Besides it is considered the ability to monitor integral core parameter – core neutron power and reactivity, – with in-core SPND detectors. It is assumed that space allocation of ICMS detectors allow to increase accuracy of measuring of these parameters during spatially irregular dynamic processes.

3. DESCRIPTION OF THE PROCESS. METHOD OF ANALYSIS

In the paper dynamic performance of the VVER-1000 core and ICMS detectors response is observed by means of the example of the real process that happened at November 16, 2005 on the Unit 5 of Kozloduy NPP. At the 15^{th} fuel cycle, with the power level of ~ 2840 MWt (t), the control rod in cell 41 from bank 10 dropped down to the lowest position. Initial position of CRs from bank 10 was 82% from the core bottom, period of CR 41 drop was ~ 2 seconds. After ~ 3.5 minutes the withdrawal of CR started, with standard velocity of 2 (sm/second). The graphs of CRs positions and the core power in course of the process presented on Figure 2.

For analysis and comparisons the experimental signals obtained by the system during process and filtered, and the results of imitation of the process were used. As an experimental data we considered SPND signal without any time performance transformations – $J_0(t)$; signals processed by corrective filter – $J_{corr}(t)$, and signals with Kalman filtering – $J_{Kalman}(t)$. Signals of $J_0(t)$ and $J_{Kalman}(t)$ obtained directly from ICMS where the processing by Kalman filter with fixed settings embedded in the hardware. Signals of $J_{corr}(t)$ obtained by special technique from $J_0(t)$.

For the imitation of parameters of the core in course of observed process the special version of 3-dimensional dynamic code NOSTRA was utilized [3], with modules for modelling of SPNDs signals and ex-core ion chamber readings.

4. RESULTS OF MEASUREMENTS AND IMITATION; PROCESSING EXPERIMENTAL DATA; COMPARISONS

Signals of three SPNDs, allocated in FA 29 (next to FA with dropping CR) during the process with CR dropping and it subsequent withdrawing, presented on the Figure 3. For each of three detectors (upper, middle and lower) signals without filtering $J_0(t)$ and with Kalman filtering $J_{Kalman}(t)$ are shown. Significant effect of filtering observed at all parts of the graphs.

Possibility of utilization of filters of different type to eliminate delay illustrated on Figure 4. The signal of the middle detector in FA 30 (next to FA with dropping CR) without filtering and processed by corrective and Kalman filters are presented. As it seen from the graphs, both of filtered signals almost similarly represent the time behaviour of the neutron flux. Significant noise of the signals from corrective filter could be explained with specific discrete form of input signal of $J_0(t)$ and with a property of the corrective filter to amplify the noise.

History of the neutron flux during process with CR dropping presented in Figure 5 in more details. For three detectors (upper, middle and lower) situated in FA 40 (next to FA with dropping CR), signals processed by Kalman filter – $J_{Kalman}(t)$ and imitation results of the neutron flux in the same positions are shown. As it seen, there is an agreement in time performance of measured and modeled signals, but differences exist, especially the systematic time shift that leads to small delay of filtered signals. It is supposed that it is mostly explained by the enquiry frequency of detector signal by ICMS (once in 160 ms), while the CR dropping duration was only 2 seconds, and the neutron flux has changed with velocity of ~15 % per second. Other reasons of model-experiment deviations are some uncertainty in axial position of the detectors, model uncertainties and, of course, time performance of the filter.

Histories of integral parameters – core neutron power and core reactivity, - and possibility to measure it with in-core monitoring system were of special interest. Figure 6 presents results of imitation of the reactivity meters readings that use signals of ex-core ion-chambers, the graph of exact reactivity during the process and calculated efficiency of the CR. Reactivity meters readings differ from the exact reactivity graphs because of spatial irregularity of disturbance and action of the feedbacks.

To control the neutron power history the general signal of all in-core detectors can be utilized, if processed each detector’s signal with Kalman filter to eliminate the delay. We use two type of SPND signals sum – signals of all detectors were summarized with equal weights, or signals of all detectors were summarized with weights in accordance with importance function in a final state (as it was proposed in [2]). Figure 7 presents the result of reactivity calculation with these two types of SPND signals’ sum, and the graph of the core reactivity calculated with 3d code also presented. A good agreement of three graphs is observed, but, as previously noted, measured curves are affected by too big time steps of the experimental data, so the minimum value of reactivity on the experimental curves are higher than calculated.

5. CONCLUSIONS

Analysis of signals of in-core monitoring system during the control rod drop at Unit 5 of Kozloduy NPP and of the result of imitation of that process with 3D code allow to affirm that methods applied for elimination of the delay in SPND signals (based on Kalman filter or corrective filter) are suitable for monitoring of fast transient in the core.

Integral signal of all ICMS detectors filtered to eliminate the delay, allows monitoring of the core neutron power in course of transient, and this signal entirely appropriate for the reactivity calculation. It could be useful for the process with significant irregularity of disturbances where spatial effects deposit essential error in the result of reactivity measurement with ex-core ICs. To assess possibility of using SPND integral signal in the reactor experiments (for instance for CR or scram efficiency) some additional research is necessary to carry out.

REFERENCEES

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2. Tsyganov S.V., Shishkov L.K., Dementiev V.G. Accounting of spatial effects in the measurements of control rod worth at power levels - 14 Symposium AER, Espoo, Finland, September 2004.

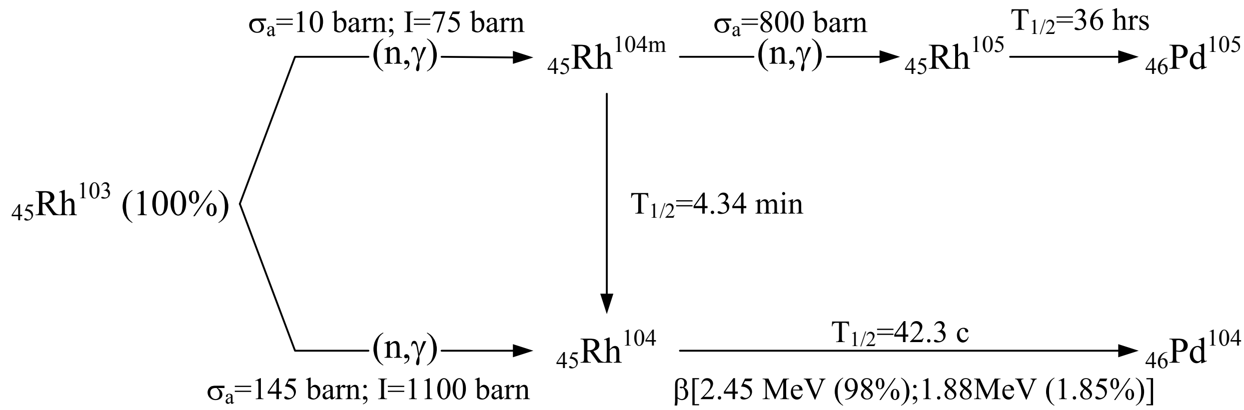

Figure 1. Nuclear reactions in the rhodium emitter.

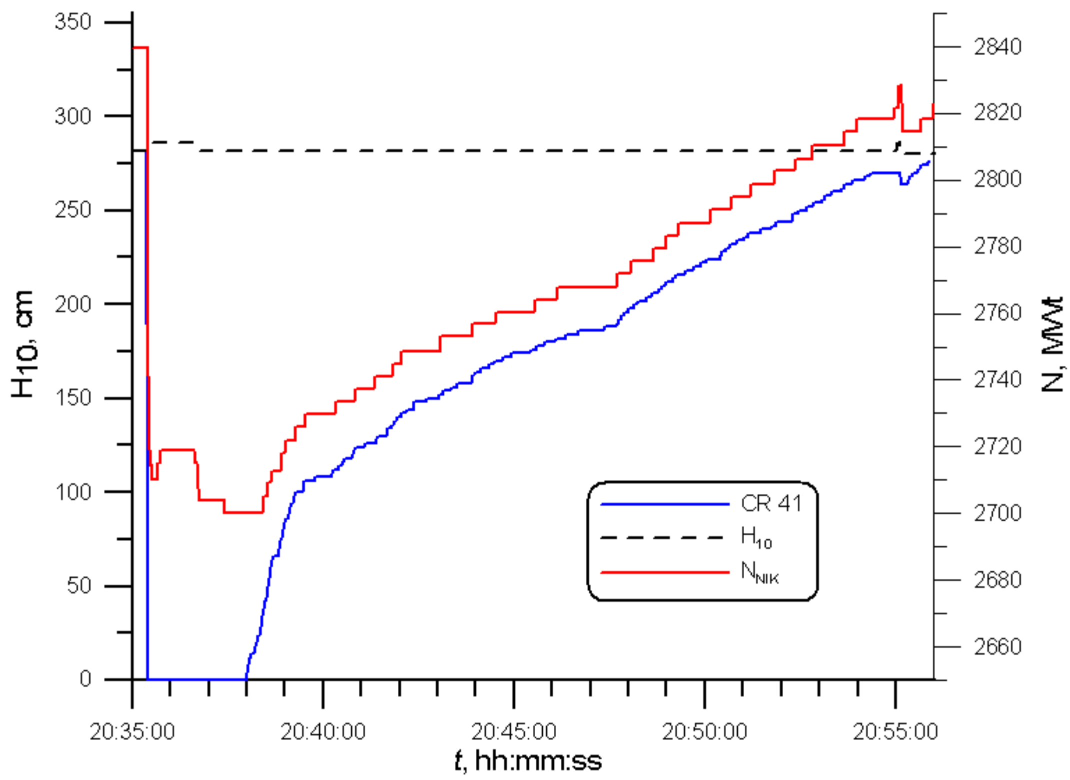

Figure 2. Control rods position and the core neutron power (by ex-core detectors) in course of the process with rod drop.

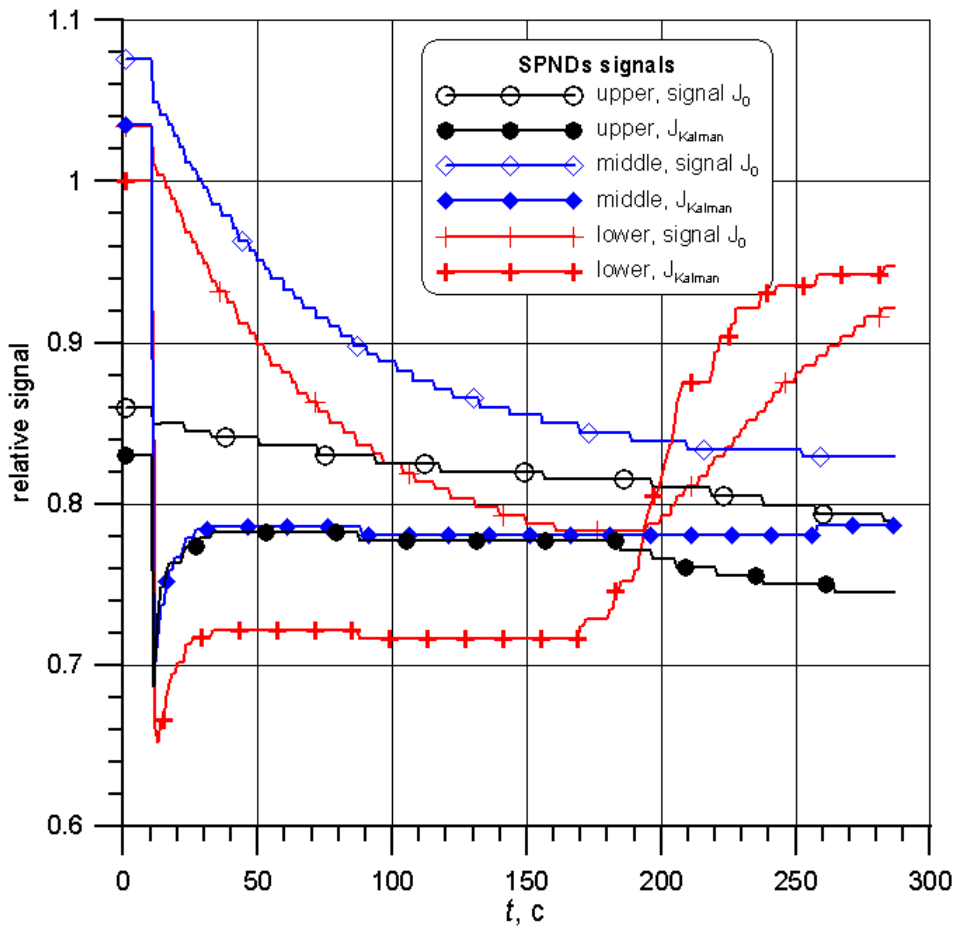

Figure 3. SPNDs signals in the cell 29 in course of the process with rod drop, 'as it is' and with Kalman filter processing.

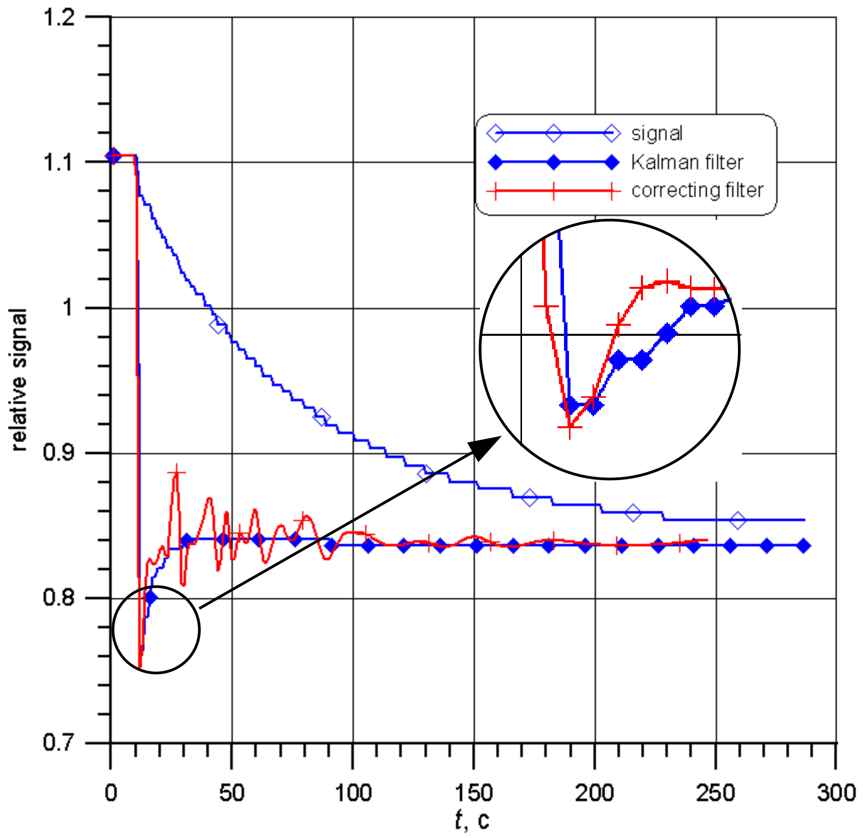

Figure 4. SPND signals in the cell 30 in course of the process with rod drop , ‘as it is’, with Kalman filter processing, with corrective filter processing.

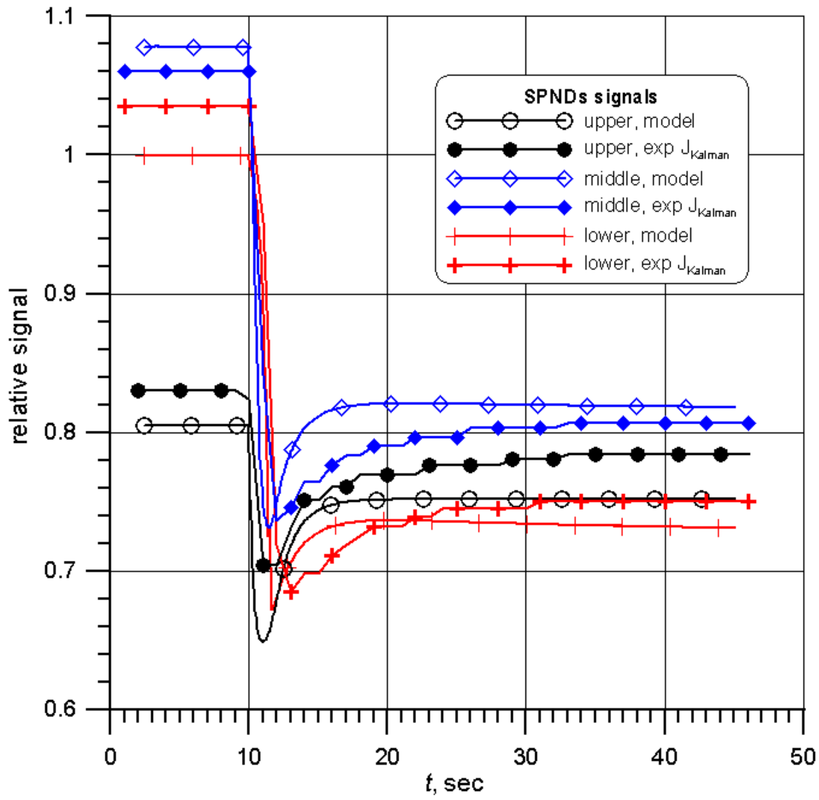

Figure 5. Neutron flux in the SPND location in the cell 40 in course of the process with rod drop, SPND signals with Kalman filtering and results of modelling.

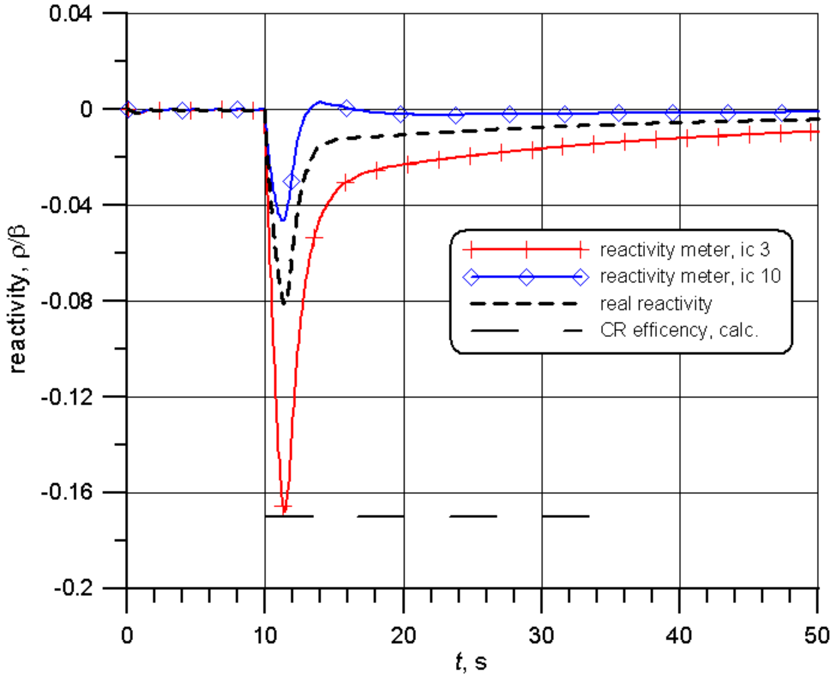

Figure 6. Rod drop process imitation. Reactivity history by the readings of ex-core ion chambers, by the 3D dynamic calculation; CR calculated efficiency.

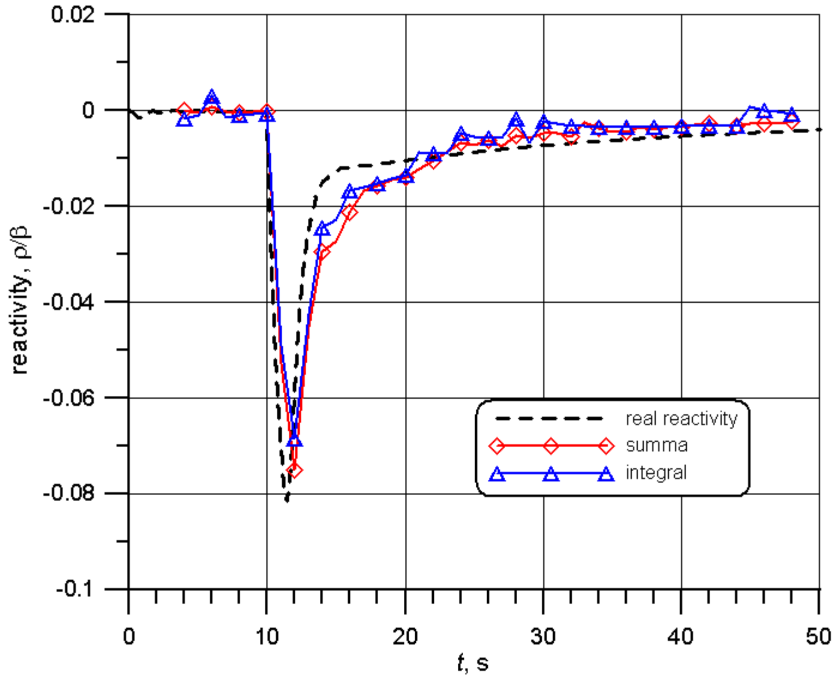

Figure 7. Reactivity history in course of the process with rod drop, obtained by dynamic calculation, and by processing of the integral signal of all SPNDs with Kalman filter.