REACTIVITY AND DISTRIBUTED NEUTRON DYNAMIC FOR THE VVER CORES

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Analysis of experimentally recorded a behavior distributed of neutron flux density (DNF) [1,2] in RRC KI required more detail consideration of methodical base and approximations, which used for description of the behavior. Mathematical models and main features of transients are based on adiabatic approximation [3]. This approximations and term "reactivity" used for description of DNF transients in reactor cores and volumes containing fissile materials are discussed.

To know the reactivity value is necessary but not sufficient to the description this process: sometimes the value is uninformative, incorrect calculation and using of it could result to unreal presentations of localization, duration and velocity of distributed DNF transients. Value of reactivity have large errors for reasons of approximations: methodical, measuring and total effect models.

ADIABATIC APPROXIMATION

Adiabatic approximation for solution of the neutron diffusion equation is [4,5]:

$$\partial\Phi/\partial\tau = (-D - A + F)\,\Phi + S, \qquad (1)$$
$$\text{where}$$
$$S = v\,(-\,\partial C/\partial\tau + Q). \qquad (2)$$
$$[-D - A + (1-\rho)F]\Phi = 0, \qquad (3)$$
$$\partial\Phi/\partial\tau = \rho F\Phi + S, \qquad (4)$$

$$\Phi(r,E,\tau) = \mathbf{1}\,R(r,E,\tau)\,\phi(r,E,\tau), \qquad (5.1)$$

$$[-D - A + (1-\rho)F]\,\phi = 0, \qquad (5.2)$$
$$\partial R/\partial\tau = R\,(\rho F - \partial\phi/\partial\tau/\phi + S/\Phi); \qquad (5.3)$$
$$\text{if } R = \exp(\rho\tau/\,l), \text{ then}$$
$$\rho = (l/\tau)\,{}_0\!\int^{\tau}(\rho F - \partial\phi/\partial\tau/\phi + S/\Phi)\,d\theta, \qquad (5.4)$$

Solution of equations (1) - (4) is function (5.1). Equations (5.2) and (5.3) for $\phi(r,\tau)$ and $R(r,\tau)$ are received, accordingly, from equations (3) - (4) and should satisfy to them. That solution provide description of DNF transients for almost all stages of transients in the reactor cores and volumes which content fissile materials. This fact was shown in experimental data [1, 2, 6] and fig's Appendix A. The determinations of basic phases and stages of transient caused by single disturbance for the reactor core have been introduced in the papers [4, 5, 6].

If $Q = 0$, then solutions of equations (5) have follow peculiarities:

1) $\phi(r,\tau)$ and $\rho(\tau)$ change by time as coefficients of equation (1) without taking into account duration of distribution $\phi(r,\tau)$ and value of $\rho(\tau)$ for sterilization;

2) $\phi(r,\tau)$ and $\rho(\tau)$ are not depend on S;

3) $R(r,\tau)$ may be presented as $R(r,\tau) = \exp(\rho(r,\tau)\,\tau/l)$, where $\rho(r,\tau)$ is parameter (5.4), showing local balance of neutron generation and losing. The parameter degenerates in ρ for the stable transients;

4) is supposed that $D(R(r,\tau)\,\phi(r,\tau)) = R(r,\tau)\,D\phi(r,\tau)$;

5) diffusion operator does not consider diffuse neutrons of source S;

The terms ρ and l are introduced formally:

$$\rho = \iint \Phi(-D-A+F)\Phi \, drdE \, / \iint \Phi F\Phi \, drdE = \quad (6.1)$$

$$= l \iint \Phi(-D-A+F)\Phi \, drdE \, / \iint \Phi\Phi \, drdE = \quad (6.2)$$

$$= \iint (\partial\Phi/\partial\tau - S)\Phi \, drdE \, / \iint \Phi F\Phi \, drdE = \quad (6.3)$$

$$= l \iint \Phi([\partial\Phi/\partial\tau]/\Phi - S/\Phi)\Phi \, drdE \, / \iint \Phi\Phi \, drdE = \quad (6.4)$$

$$= l \iint \Phi(\partial\Phi/\partial\tau)drdE \, / \iint \Phi\Phi drdE + l \iint \Phi v(\partial C/\partial\tau)drdE \, / \iint \Phi\Phi drdE -$$

$$- l \iint \Phi vQdrdE \, / \iint \Phi\Phi drdE = \quad (6.5)$$

$$= l \iint \Phi(\partial\Phi/\partial\tau)drdE \, / \iint \Phi\Phi drdE + \beta_{*\phi\phi} - \iint \Phi v(\sum_i \lambda_i \, C_i)drdE \, / \iint \Phi\Phi drdE -$$

$$- l \iint \Phi vQdrdE \, / \iint \Phi\Phi drdE \quad (6.6).$$

$$\Gamma^1 = \iint \Phi F\Phi \, drdE / \iint \Phi\Phi \, drdE = \iint \Phi v \, v\Sigma_f \Phi \, drdE / \iint \Phi\Phi \, drdE, \quad (7.1)$$

$$\beta_{*\phi\phi} = \iint \Phi\Sigma_i\beta_i F\Phi drdE / \iint \Phi F\Phi \, drdE. \quad (7.2)$$

$$C_{i*\phi\phi} = \text{A} \iint \Phi C_i \, drdE / \iint \Phi\Phi/v \, drdE, \quad (7.3)$$

$$\partial C/\partial\tau = (\beta_{*\phi\phi} / l) \, \Phi - \sum_i \lambda_i \, C_{i*\phi\phi} \quad (7.4)$$

They are not connected with problem content of mathematical models, but they correspond to terms reactivity and average life-time neutron in core by physical content of adiabatic approximation.

The inverse kinetics equation for reactivity is received from equation (6.4) in classic form, when $S = - v \, \partial C/\partial\tau$ (See Appendix B):

$$\rho(\tau) = l(\partial\Phi(\tau)/\partial\tau)/\Phi(\tau) + \beta_{*\phi\phi} - \sum_i f_i(\tau) \, \beta_i \, / \, \Phi(\tau) - l \, v(\tau)Q(\tau) \, / \, \Phi(\tau), \quad (8.1)$$

$$f_i(\tau) = [l\lambda_i/\beta_i] \, C_i(\tau). \quad (8.2)$$

Transients of DNF have follow phases (the phases are determinated by arguments of $R(r,\tau)$ and $\varphi(r,\tau)$):
1) $R(r,\tau)$ and $\varphi(r,\tau)$ - disturbance,
2) $R(r,\tau)$ and $\varphi(r)$ - stabilization,
3) $R(\tau)$ and $\varphi(r)$ - steady transient,
4) $R(\tau)$ and $\varphi(r,\tau)$ - quasistatic approximation.

SUBCRITICAL CONDITION

If $Q \neq 0$ but $\partial Q/\partial\tau = 0$, then two states of the reactor cores and volumes with fissile materials and sources are interested.
1) $\rho = 0$ - state is critical accordance with the definition (4). but DNF is increased from neutron sense S which have not been take into account in right part equation (1) and consequently in reactivity;
2) $\partial\Phi/\partial\tau = 0$ - state of the core is subcritical accordance with the definition (4), but DNF is constant. Then

$$[-D - A + (1-\rho)F] \, \varphi = 0, \quad (14)$$

$$\partial\Phi/\partial\tau = \rho/l \, \Phi + v \, Q. \quad (15.1)$$

$$\Phi = - Sl/\rho \text{ or } \rho \, \Phi = - SL \quad (15.2)$$

This equations corresponds to important property of subcritical the reactor cores and volumes of fission materials which contents sources and allow to create methods for determination values of subcriticality and intensity of the source.

So it possible calculate of total intensity source

$$Q_{*\phi\phi} = \iint Q\Phi drdE \, / \iint \Phi drdE = - \rho/l \iint \Phi\Phi drdE \, / \iint v\Phi drdE. \quad (15.4)$$

If $Q \neq 0$, $\partial Q/\partial\tau \neq 0$ then using equations (6.3) - (6.6) allow to determinate value of reactivity by methods of moving sources or moving elements of the cores, in particle, by inserting determine disturbance of reactivity.

NONLINEAR DYNAMIC SYSTEM FOR POWER REACTOR

Dynamic system which describes dynamic of DNF(Φ), behavior of isotope composition (X) and process parameters (Y) in the core is follow:

$$\partial\Phi/\partial\tau = (-D - A + F)\,\Phi + S, \qquad (16)$$
$$\partial X/\partial\tau = f_x(\Phi, X, Y, N, Q, t, \tau),$$
$$\partial Y/\partial\tau = f_y(\Phi, X, Y, N, Q, t, \tau)$$

and correspondence initial and boundary conditions.

Naive using of the adiabatic approximation leads to problems connected with homogeneous and dynamic equations corresponding to equation (16):
- what are effects kept in homogeneous equation and what - in dynamic? Incorrect description of the effects leads to inadequate description of disturbance DNF, values, time, duration and velocity influence of the effects;
- does the homogeneous equation remain self-conjugate?
- does formula (6) valid for solution of homogeneous equation or it should be increase number of terms in the function-solution?

ERRORS OF REACTIVITY CALCULATION

Formulae (6) are get for calculation of reactivity values within scope of adiabatic approximation and have all it restrictions. Errors of experimental and calculated reactivity values for critical states of core are differ up to two hundred times.

Methodical errors
The errors may be explained by, in particular, follow reasons:
- full agreement of mathematical model and the core configuration, structure and state is not achieved;
- restrictions of solution equations (1) - (2) and the approximation have influence on value errors;
- formal conditions of derivation formulae (4) are not met;
- neutron-physical coefficient values of (1) - (2) equations and the inverse reactor equation (local and the over core parameters: l, v, β_{eff} and so on) are not agreed;
- the time for calculated values of reactivity and stages of transient are not agreed, in particle, agreement of DNF distribution;
- account of some parameters in DNF is not correct:
. nonlinearity of the reactivity functional is obviously for large and many-parametrical disturbances;
. reactivity coefficients are calculated for sigle-parametrical disturbances should not be used for calculating of total reactivity for many-parametrical and nonadequate states of the cores;
. if effects of DNF disturbance are described by reactivity coefficients, localization and
duration of DNF distribute are false. It influents for very localized and fast disturbances spreads on over the core and it local effects are decreased and it duration are prolonged.

Errors of measurement
Reactivity values, which calculated by reactivity meters (Appendix A), are equal to the reactivity of formulae (6.1) and (6.2) only when transients has stage of the stable transient.
The errors of calculated reactivity values determined by registered DNF may be caused:
- by instrumentation and calculation errors;

- by background influence, spectral sensitivity and alter sensitivity of ionization cambers during operation;
- by nonadequte placing of reactivity meters ionization cambers. It causes "space effects of reactivity" by nonuniform change of DNF. Reactivity meters sense only the neutrons, which absorber by ionization cambers, but the neutron subregion "existence" and informativity don't correspond to mathematical model;
- by nonadequte composition, structure and state of the core to reactivity meter mathematical model;
- calculated reactivity values depend on accuracy of used values of fractions delay neutrons even for states of the core when contribution of delay neutron sources change in DNF process is neglect.

Calculation errors for total effect reactivity of few parameters

- measurement errors of processing parameters;
- nonadequte value of reactivity coefficient;
- nonlinear of mathematic model for total reactivity;
- violation of localization and time take effect of disturbance.

References

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2. Ionov V. S., Krainov Yu.A. Safety of WWER and Space-Time Kinetics Investigation of the core. WANT. RRC KI. Series :Nuclear Reactors Physics. Iss. 4. Moscow. 1994 (In Russian).
3. Hetrick D. L. DYNAMICS OF NUCLEAR REACTORS. Chicago, London. 1970.
4. Ionov V. S. Reactivity and Neutron Dynamic. "Atomic Energy". V. 77, iss. 4, 1994. Moscow (In Russian).
5. Ionov V. S. Distributed Neutron Dynamics of WWER Type Cores. Preprint IAE - 5964/4. RRC KI. Moscow. 1996 (In Russian).
6. Ionov V. S., Krainov Yu. A., Shiskov L. K. and etc. NOSTRA CODE VERIFICATION WITH USING TRANSIENTS INITIATED BY VVER CONTROL ROD MOVEMENT. Proc. eight Symposium of AER. Czech Rep. 21 - 25 Sept. 1998.

Behavior distributed of neutron flux density VVER-1000 core

involved by motion of control rods

Fig. 2 - 5. Motion group of control rods without reactivity compensation.

Fig. 6 - 9. Five control rods of group is about 40% core height. Alone control rod of the group is being inserted in core to the height.
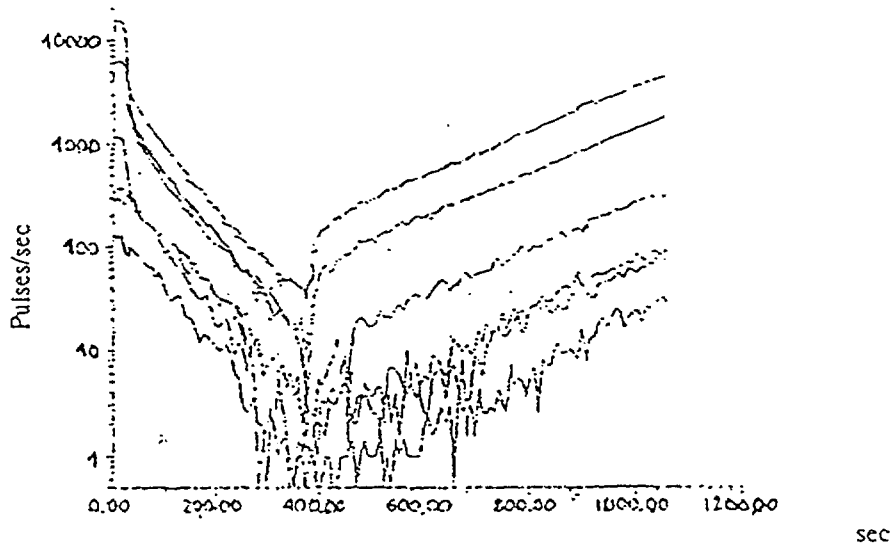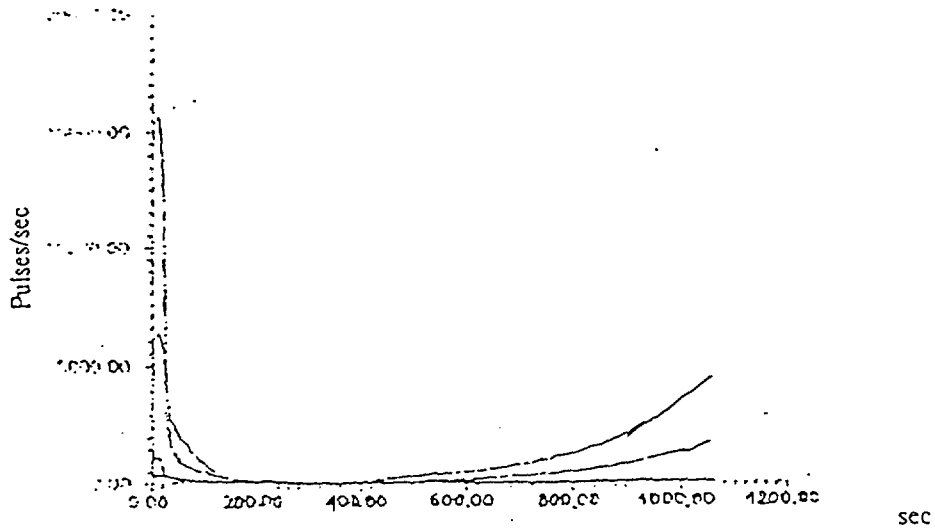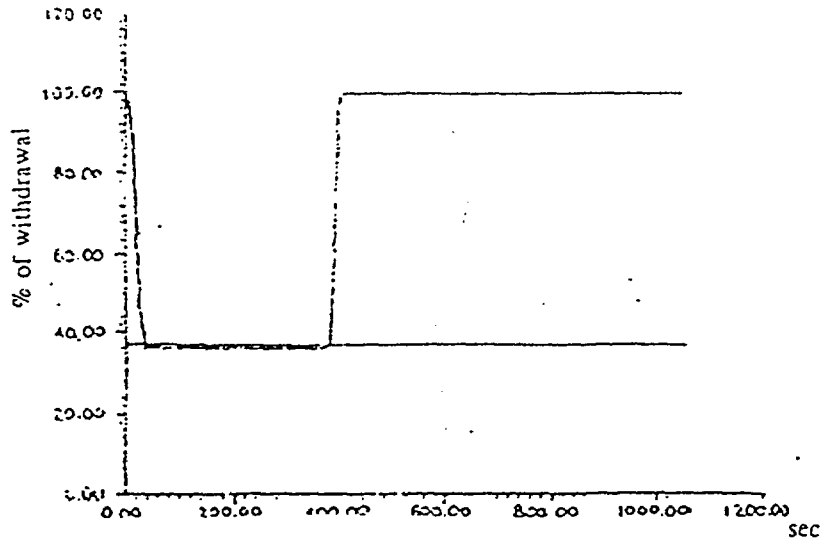
Fig. 10 -13. Motion group of control rods when reactivity is being compensated.

Fig. 14 - 17. Simulated of scram. One group is hanging up.

Fig. 18 - 21. Motion of alone control rod.

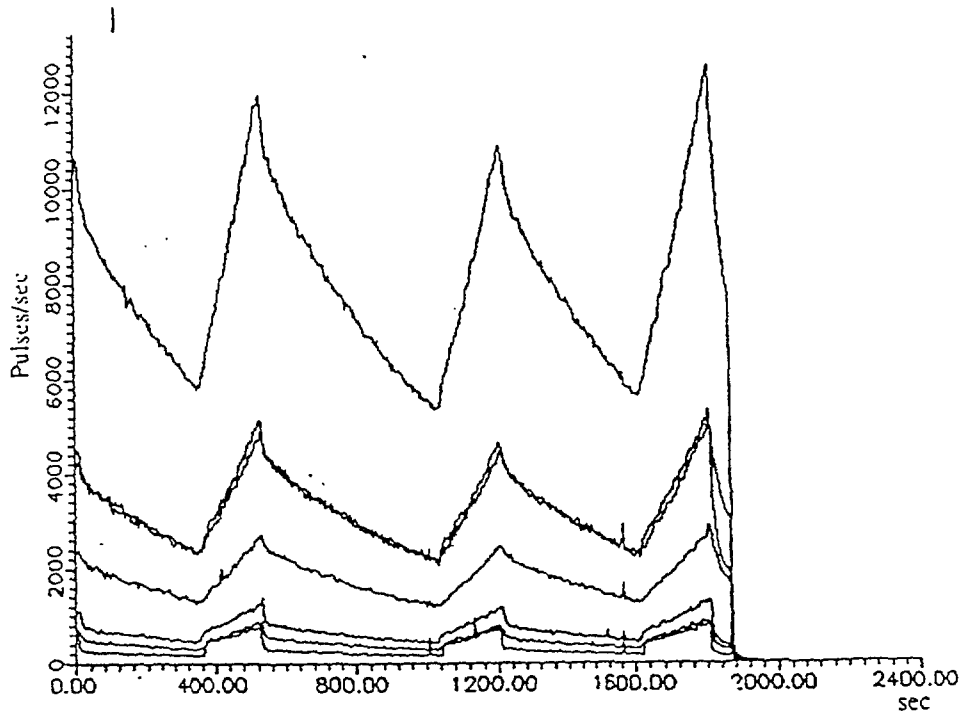# Fig. 2 - 5. Motion group of control rods without reactivity compensation
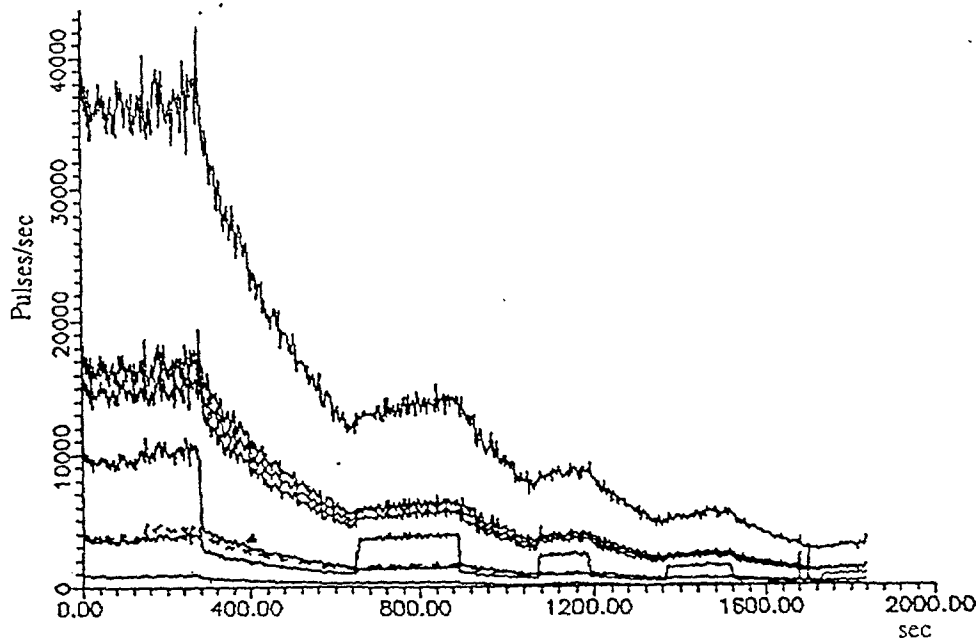
Fig. 2. Detector reading. Unnormalized.
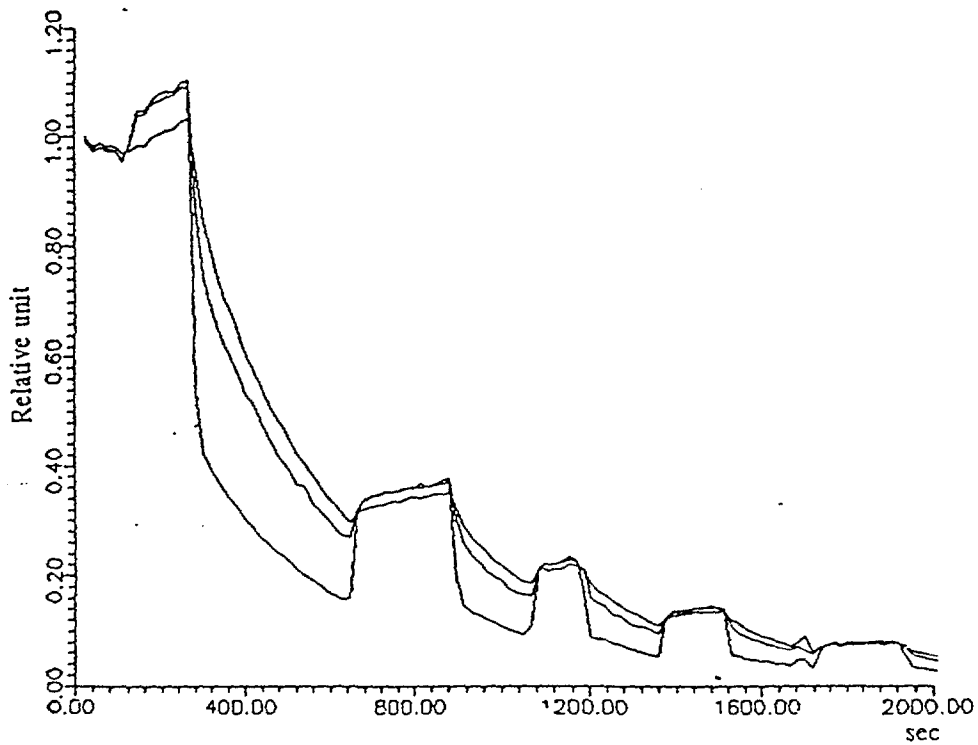
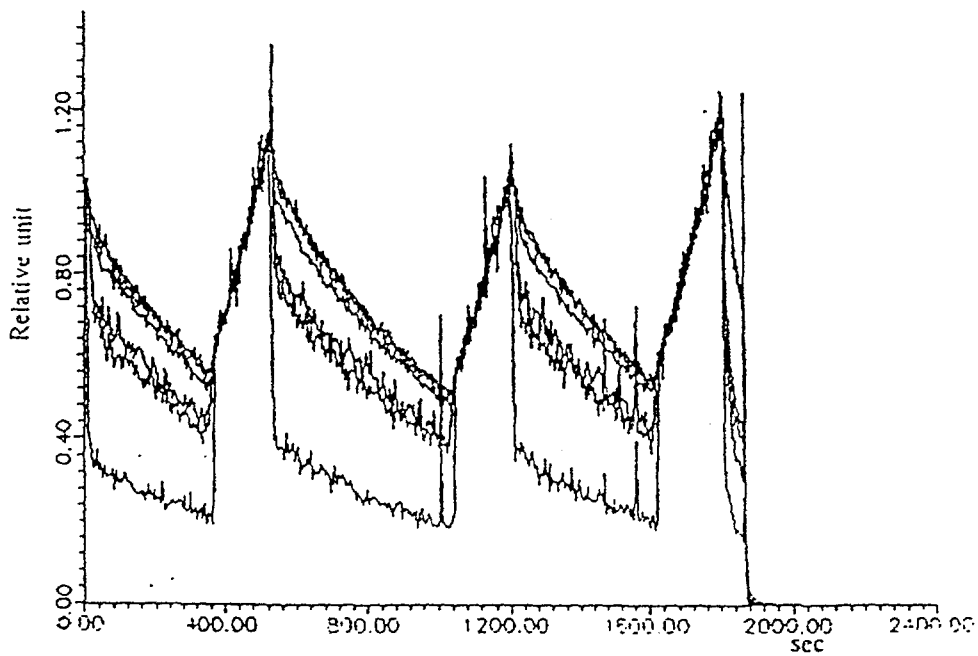Fig. 3. Detector reading. Normalized "1.0 at initial".

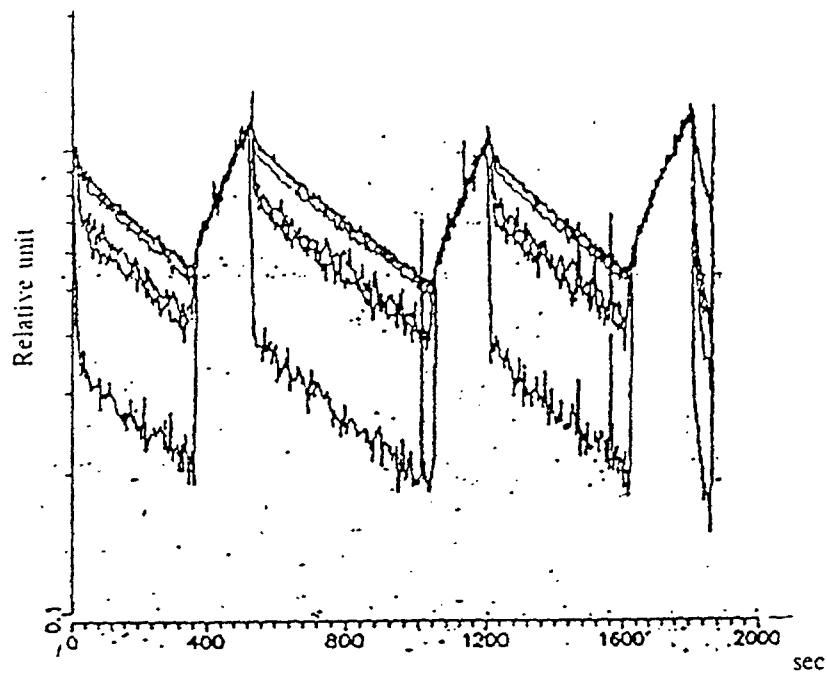# Fig. 2 - 5. Motion group of control rods without reactivity compensation
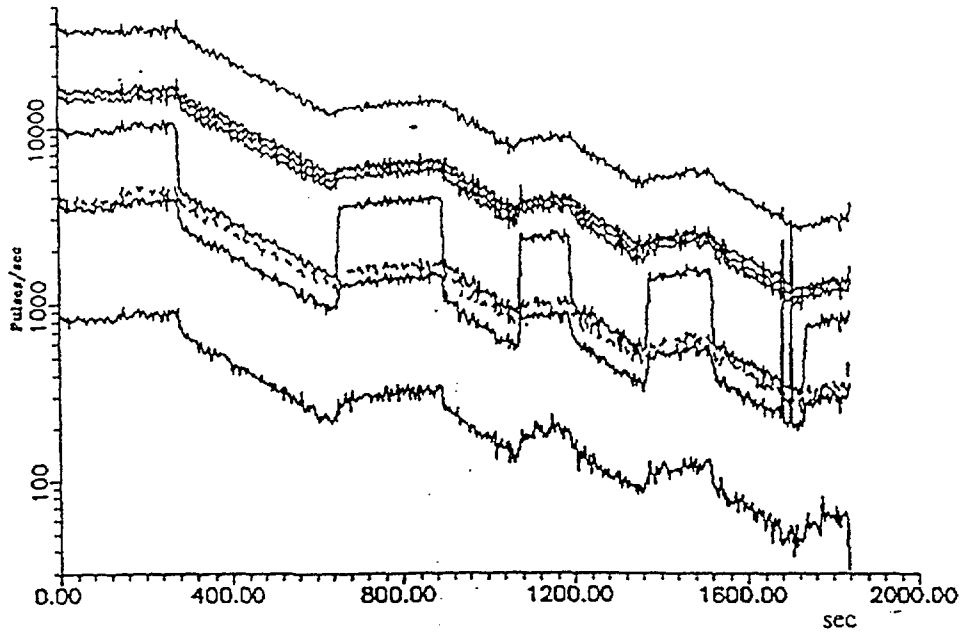
Fig. 4. Detector reading. Unnormalized. Semilogoritmical coordinates.
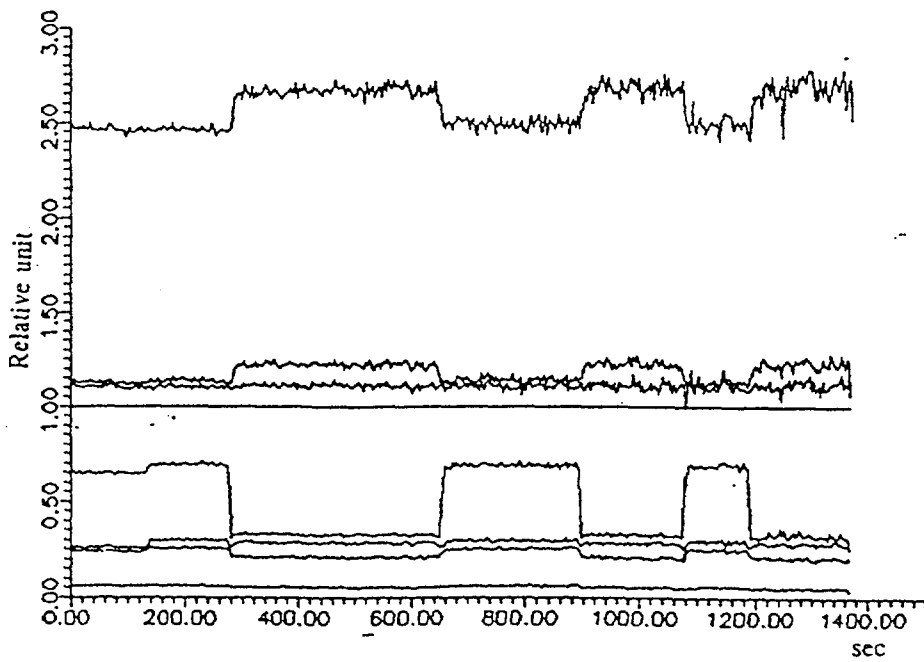
Fig. 5. Ration of detector reading. Normalized: divided at the reading of the one detector.

Fig. 6 - 9. Five control rods of group is about 40% core height.
Alone control rod of the group is being inserted in core to the height

Fig. 6. Detector reading. Unnormalized. Semilogoritmical coordinates.

Fig. 7. Detector reading. Unnormalized.

Fig. 6 - 9. Five control rods of group is about 40% core height.
Alone control rod of the group is being inserted in core to the height.

Fig. 8. Control rods positions and motion of alone rod.
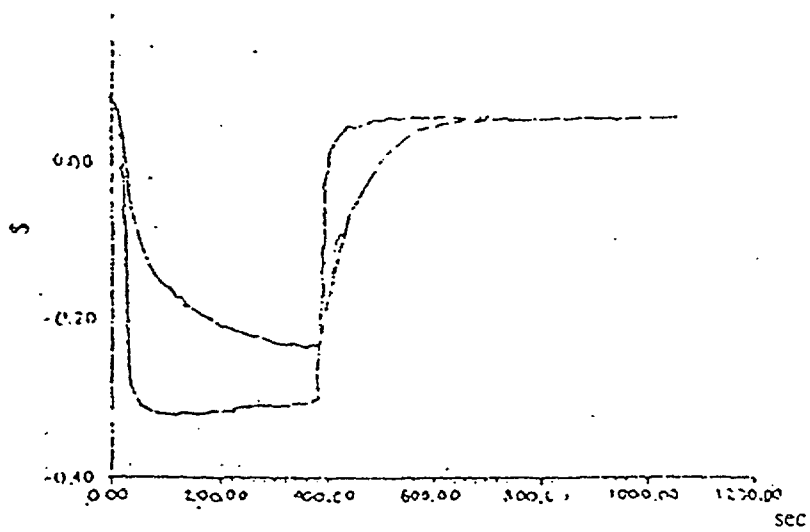
Fig. 9. Reading of two reactivity-meters.

Fig. 10 -13. Motion group of control rods when reactivity is being compensated

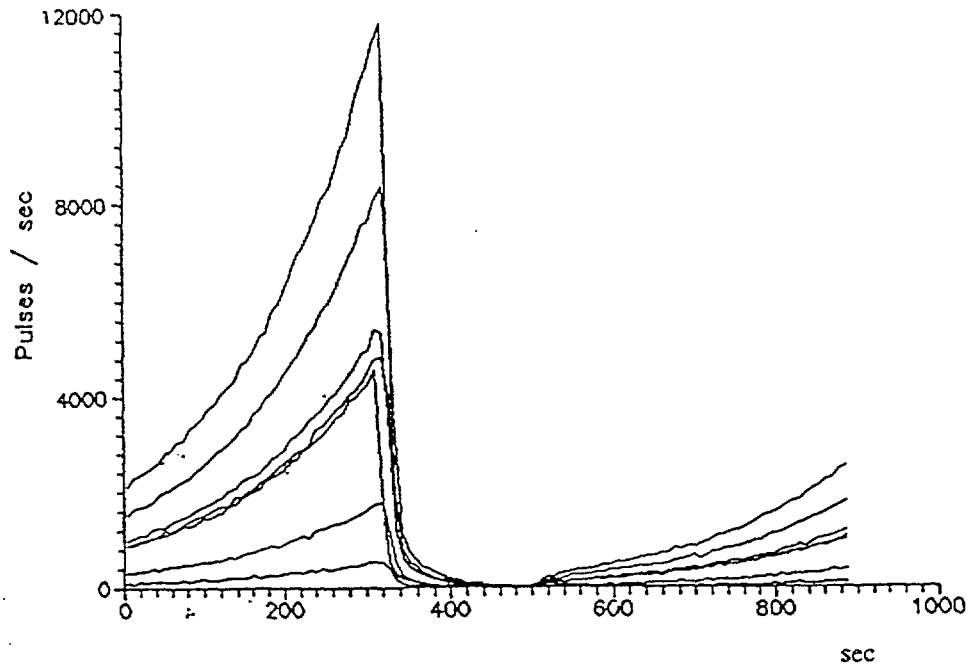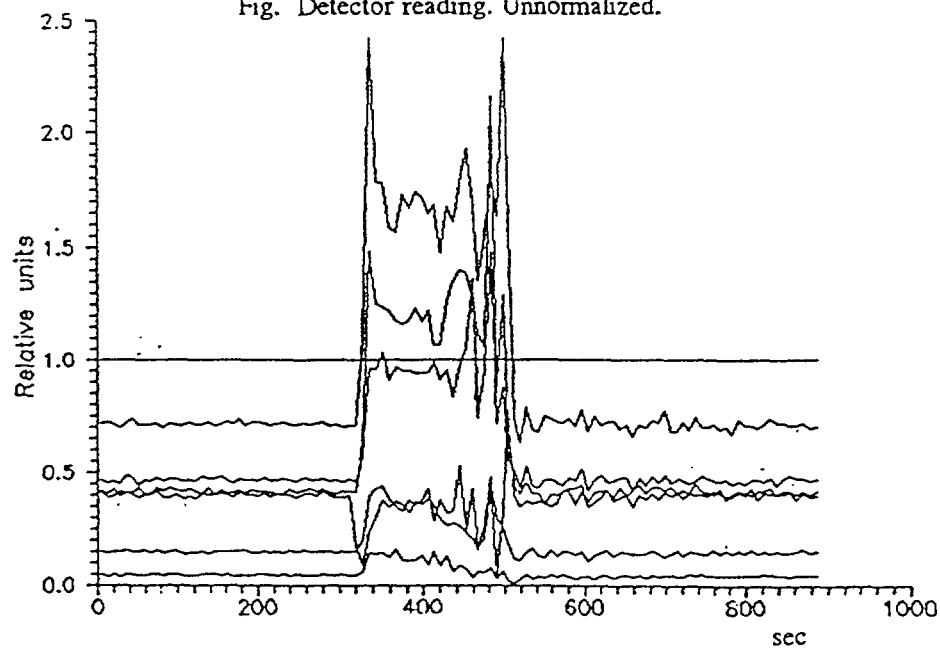Fig. 10. Detector reading. Unnormalized.

Fig. 11. Detector reading. Normalized "1.0 at initial".

Fig. 10 -13. Motion group of control rods when reactivity is being compensated

Fig. 12. Detector reading. Semilogoritmical coordinates.
Normalized "1.0 at initial".
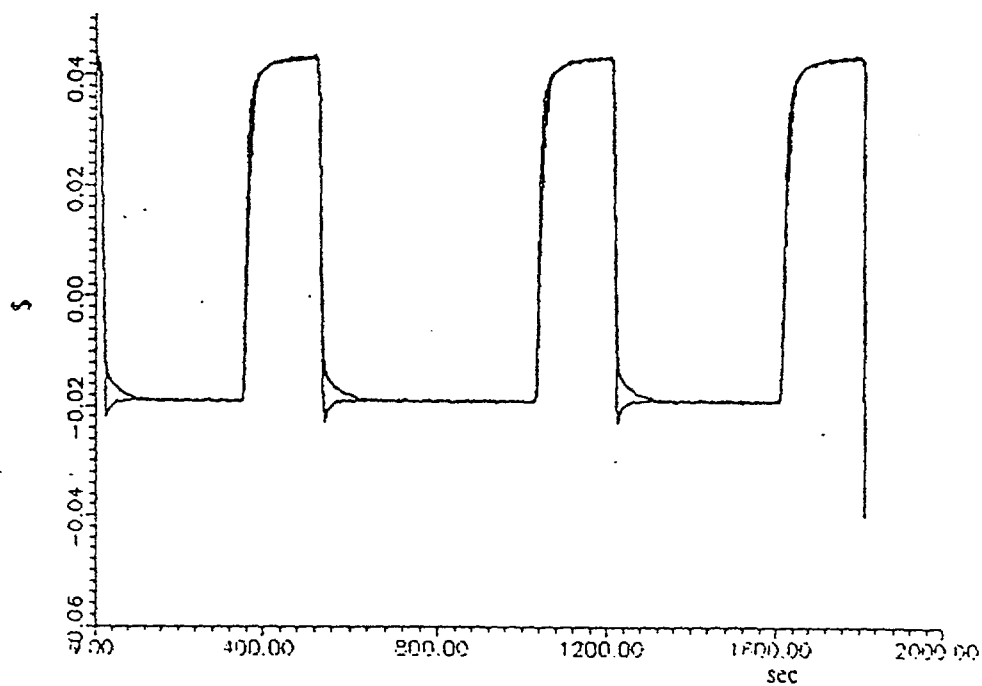
Fig. 13. Reading of two reactivity-meters.

Fig. 10 -13. Motion group of control rods when reactivity is being compensated

Fig. Detector reading. Unnormalized.

Fig. Ration of detector reading.
Normalized: divided at the reading of the one detector.
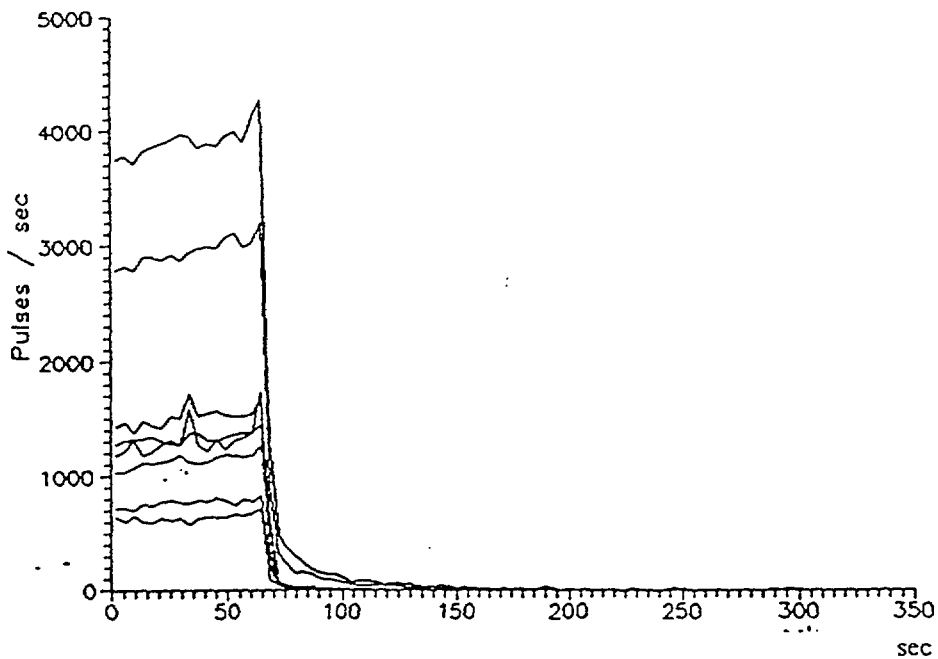
Fig. 14 - 17. Simulated of scram. One group is hanging up

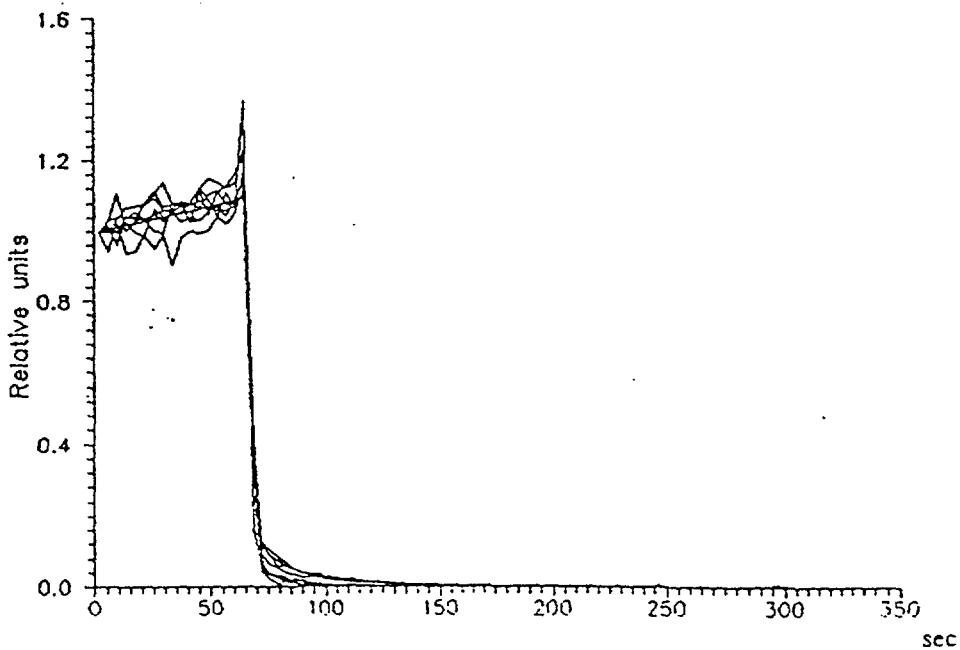Fig. 14. Detector reading. Unnormalized.

Fig. 15. In core detector reading. Normalized "1.0 at initial".

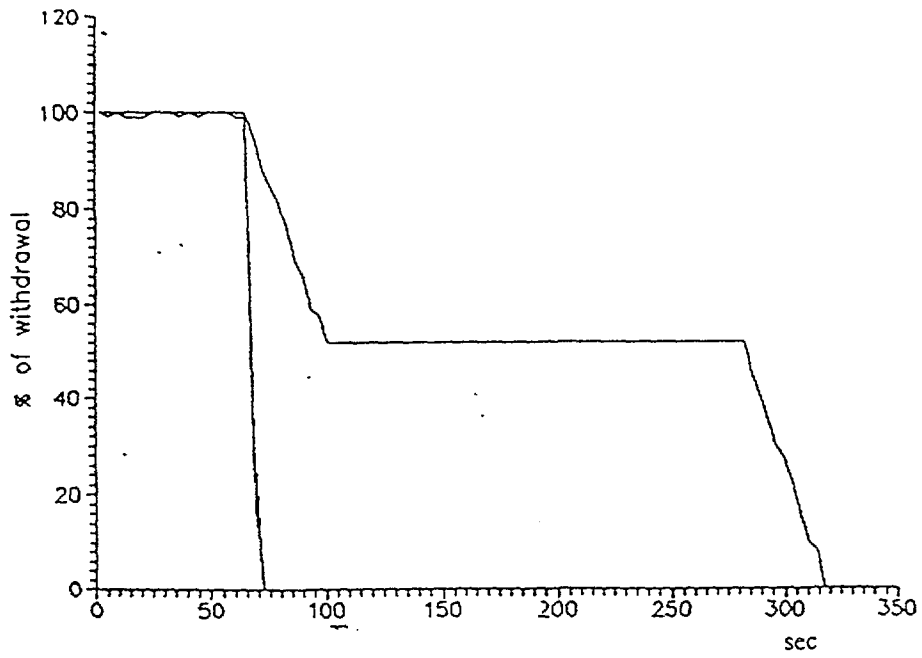## Fig. 14 - 17. Simulated of scram. One group is hanging up
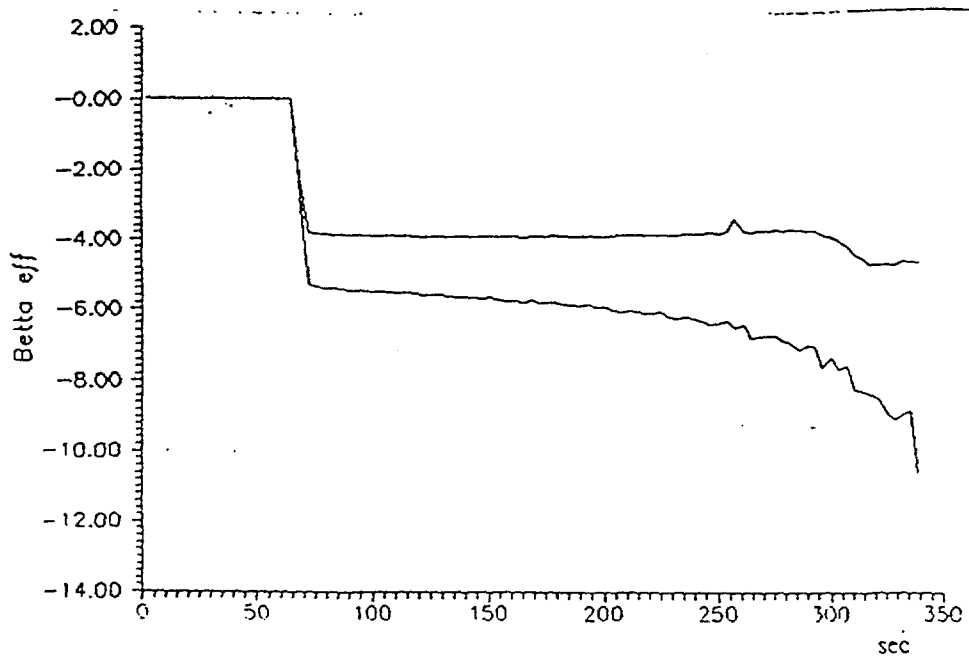

Fig. 16. Control rods motion.

Fig. 17: Reading of two reactivity-meters.

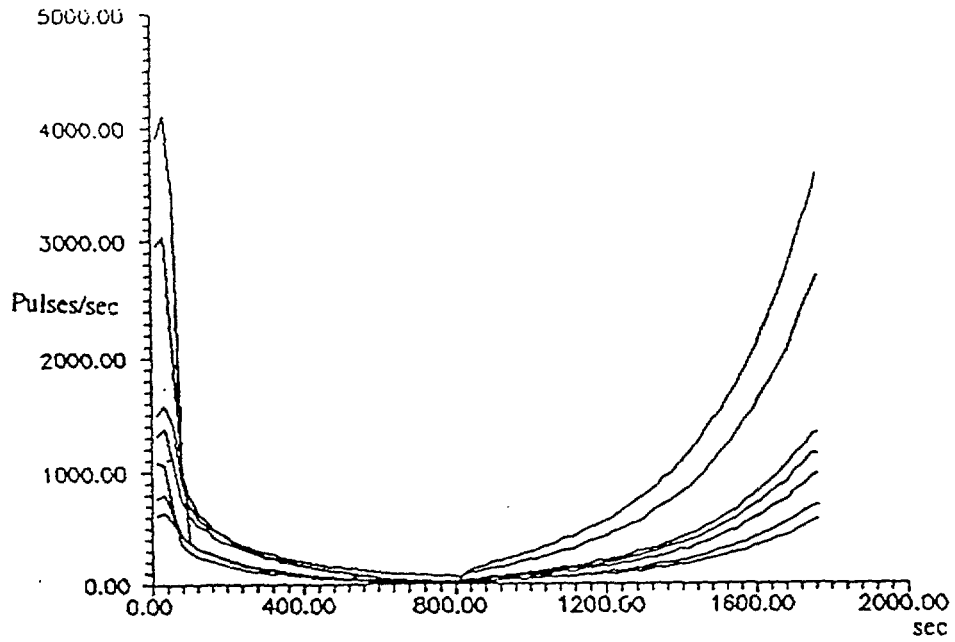# Fig. 18 - 21. Motion of alone control rod

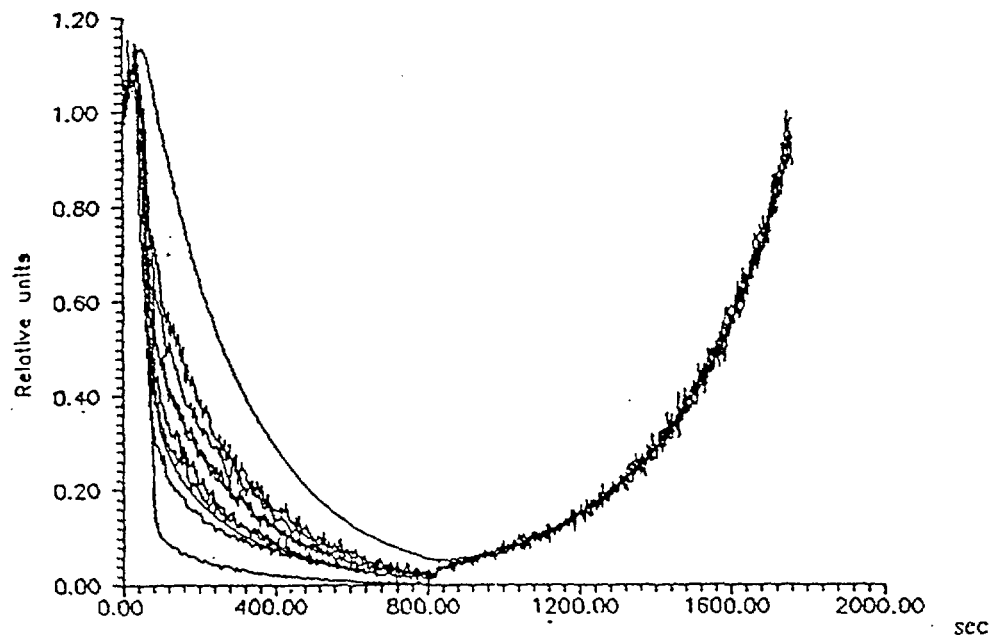Fig. 18. Detector reading. Unnormalized.

Fig. 19. Detector reading. Normalized "1.0 at initial".
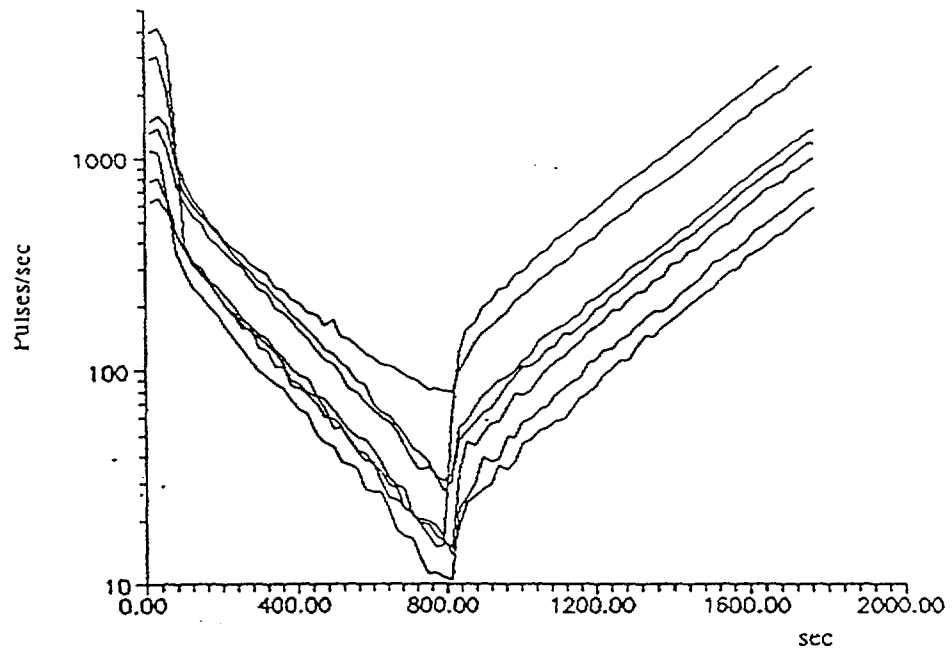
Fig. 18 - 21. Motion of alone control rod

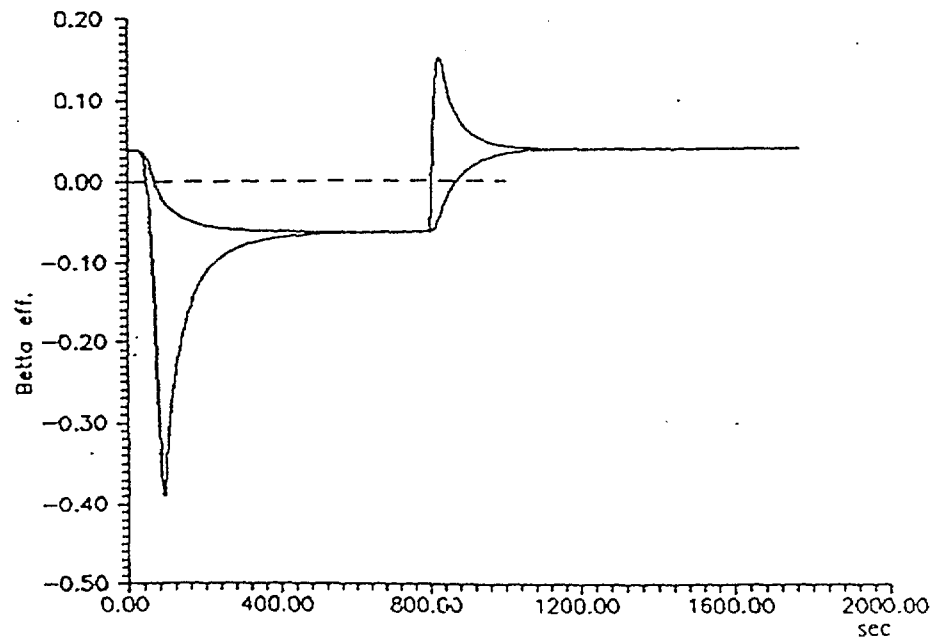Fig. 20. Detector reading. Unnormalized. Semilogoritmical coordinates.

Fig. 21. Reading of two reactivity-meters.

$$\partial n/\partial \tau = (\rho - \beta)\, n/l + \Sigma_i \lambda_i C_i + Q \quad ([3]\ 2.1),$$
$$\partial C_i/\partial \tau = \beta_i\, n/l + \lambda_i C_i \quad ([3]\ 2.2).$$

The exact solution of equation ([3] 2.2)

$$C_i(\tau) = \{C_i(0) - \beta_i\, n(0)/\lambda_i\, l\}\, exp(-\lambda_i \tau) + (\beta_i/\lambda_i\, l)\, \{n(\tau) - \int^\tau_0 \partial n(\theta)/\partial \tau\, exp(-\lambda_i\, (\tau - \theta))d\theta\}. \quad ([3]\ 4.8)$$

The inverse kinetics equation for reactivity is

$$\rho(\tau) = (l\, \partial n(\tau)/\partial \tau)/n(\tau) + \beta - l\, \{\Sigma_i\, \lambda_i\, C_i(\tau)\}/n(\tau) - l\, Q(\tau)/n(\tau) \quad ([3]\ 4.9)$$

Formula are used at reactivity meters ПИР

$$\rho(\tau) = \beta - l\, \{\Sigma\, \beta_i\, f_i(\tau)\}/n(\tau) \quad (A.1)$$

$$\rho(\tau)/\beta = 1 - \{\Sigma\, \beta_i\, f_i(\tau)\}/\beta\, n(\tau) = 1 - \Sigma B_i(\tau)\}/\beta\, n(\tau) \quad (A.2)$$
$$f_i(\tau) = f_i(\tau - \Delta\tau)\, exp(-\lambda_i \Delta\tau) - \{n(\tau) - n(\tau - \Delta\tau)\}\{1 - exp(-\lambda_i \Delta\tau)\}/(\lambda_i \Delta\tau) - n(\tau - \Delta\tau)\, exp(-\lambda_i \Delta\tau) + n(\tau). \quad (A.3)$$

$$B_i(\tau) = B_i(\tau - \Delta\tau)\, exp(-\lambda_i \Delta\tau) + A_i\, n(\tau) - D_i\, n(\tau - \Delta\tau)$$
$$B_i(0) = \beta_i\, n(0)$$
$$A_i = \beta_i\, ([1 - exp(-\lambda_i \Delta\tau)]/(\lambda_i \Delta\tau))$$
$$D_i = \beta_i[exp(-\lambda_i \Delta\tau) - (1 - exp(-\lambda_i \Delta\tau))/(\lambda_i \Delta\tau)]$$

Formula are used at reactivity meters GROUP SCHEIDER

$$\rho(\tau) = [l\, (n(\tau) - n(\tau - 2\Delta))]/(2\Delta\tau\, n(\tau)) + \beta - l\, \{\Sigma_i\, \lambda_i\, C_i(\tau) + Q(\tau)\}/n(\tau) \quad (A.4)$$
$$\lambda_i\, C_i(\tau) = C_i(\tau - \Delta\tau)\, \lambda_i\, exp(-\lambda_i \tau) + (\beta_i/l)\, n(\tau)\, [1 - exp(-\lambda_i\, \Delta\tau)] \quad (A.5)$$
$$C_i(0) = \beta_i\, n(0)\, /\, (\lambda_i\, l)$$

Exact formula

$$\rho(\tau) = (l\, \partial n(\tau)/\partial \tau)/n(\tau) + \beta - \{\Sigma\, \beta_i\, f_i(\tau)\}/n(\tau) - l\, v\, Q(\tau)/n(\tau). \quad (A.6)$$