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EVALUATING EFFECTS OF (γ,n) & (n,2n) REACTIONS ON CRITICALITY AND KINETICS OF HEAVY-WATER REACTOR

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Оценено влияние фотонейтронных реакций на критичность и динамику тяжеловодного реактора. Показано, что при нейтронно-физических расчетах ядерного реактора реальных размеров, учитывать эти реакции не требуется. Показано, что влияние запаздывающих фотонейтронных реакций на динамику тяжеловодного реактора существенно. Разработан и опробован в имитационном эксперименте цифровой реактиметр для такого реактора.

CRITICALITY

It is evident that any particular nuclear reactor under stationary conditions is always subcritical since it cannot be completely isolated from outside neutrons sources i.e. from neutrons which do not directly result from fission. If the contribution of these neutrons into neutron balance is insignificant then one can apply model of just critical reactor to real stationary reactor. In this case for example the verification of computational codes using reactor criticality experiments is facilitated.

Photoneutrons contribution

The action of gamma rays with threshold energy of E_gi2.23 MeV on the nuclei of deuterium results in monoenergetic neutrons. This is called (g,n) reaction and the neutron sources based on this reaction are called photoneutron sources. The cross section of this reaction for deuterium is: $\sigma_{\gamma,n} \approx 2\cdot 10^{-3}$ barn [1].

Since $200\ \text{MeV} \cong 32\cdot 10^{-12}\ \text{W}\cdot\text{s}$ the fission rate (N_f) in a reactor with the power E[W] will be

$$N_f = E \Big/ 32\cdot 10^{-12} \frac{\text{fissions}}{\text{s}}.$$

Accordingly the number of neutrons born in a reactor for 1 sec due to the fission is:

$$N_n = \nu \cdot N_f = \nu \cdot E \Big/ 32\cdot 10^{-12} \frac{n}{s},$$

where $\nu \approx 2.5$ is the number of secondary neutrons in one event of fission.

At the same time the number of γ-quantums (N_γ) with the energy higher than 2.23 MeV, born in a reactor with fission rate (Nf), can be determined by:

$$N_\gamma = n_\gamma \cdot \xi \cdot N_f,$$

where $\nu_\gamma \approx 7.4$ is the average yield of γ-quanta during the Uranium fission and $\xi \approx 0.02$ is the fraction of γ-quanta with the energy higher than 2.23 MeV [1].

Suppose that a cylindrical reactor with radius R and height H is almost filled with heavy water (the maximum value of (γ,n) source power has been considered). Then one can determine the power of photoneutrons source using following formula:

$$S_{\gamma,n} = N_\gamma \cdot \sigma_{\gamma,n} \cdot \rho_{D_2} \cdot \frac{2 \cdot R \cdot H}{R+H}$$

and, consequently, the reactor multiplication will be

$$\frac{1}{1-\kappa} = \frac{N_n}{S_{\gamma,n}} = \frac{\nu}{\nu_\gamma \cdot \xi \cdot \sigma_{\gamma,n} \cdot \rho_{D_2}} \cdot \frac{R+H}{2RH}.$$

It is clear that the reactor multiplication under the photoneutron source depends not on the reactor power but only on its size (the greater the size the less multiplication). It is usually accepted, that in a cylindrical reactor the relation of 2R=H is executed. Therefore the multiplication factor (k) of a stationary heavy water reactor with radius R can be estimated by:

$$k = 1 - \frac{S_{\gamma,n}}{N_n} = 1 - \frac{4 \cdot \nu_\gamma \cdot \xi \cdot \sigma_{\gamma,n} \cdot \rho_{D_2} \cdot R}{3 \cdot \nu}. \tag{1}$$

Fig.1 shows the variation of k versus reactor radius. It can be seen that within practically realistic range of reactor dimensions the effect of photoneutrons reactions on heavy water reactor criticality is not essential.

(n, 2n) Reactions Contribution

In a similar way (n, 2n) deuterium reaction effect on the heavy water reactor criticality has been evaluated. In this case one should consider the threshold of this reaction is 3.34 MeV and the cross-section is $\sigma_{n,2n} \approx 8.6 \cdot 10^{-3}$ barn [1].

For an estimation of the (n, 2n) source power it is necessary to know in one reactor spectrum the fraction of neutrons with the energy higher than the threshold. This fraction can be evaluated using a cell calculation code e.g. WIMS. The estimates show that for heavy water reactors it is approximately 1.6%. Therefore at approximately equal ξ values the (n, 2n) source is several times more intensive than photoneutron one due to higher reaction cross-section. Analogous to equation (1)

$$k = 1 - {}^{8 \cdot \xi \cdot \sigma_{n,2n} \cdot \rho_{D_2} \cdot R} \big/ {}_{3}.$$

It is seen in Fig.1 that in spite of the fact that the effect of (n, 2n) source on the reactor criticality is higher than that of photoneutrons source, it is not too high to be obligatory considered at criticality calculation in all situations.

According to equation (1), the dependence of subcriticality of a reactor on the source power is linear. Hence contributions of both (γ, n) and (n, 2n) sources into subcriticality are additive and can be calculated by

$$k = 1 - \frac{S_{\gamma,n} + S_{n,2n}}{N_n}.$$

So, according to estimates given in Fig.1, even a very large heavy water reactor with radius of (e.g.) five meters will have subcriticality less than 0.12%. In particular, the ZPR critical assembly with vessel radius 1.19 m has in the steady state subcriticality less than 0.032%. The obtained estimations of heavy water reactor subcritiality in steady state are within an accuracy of calculation and experimental methods.

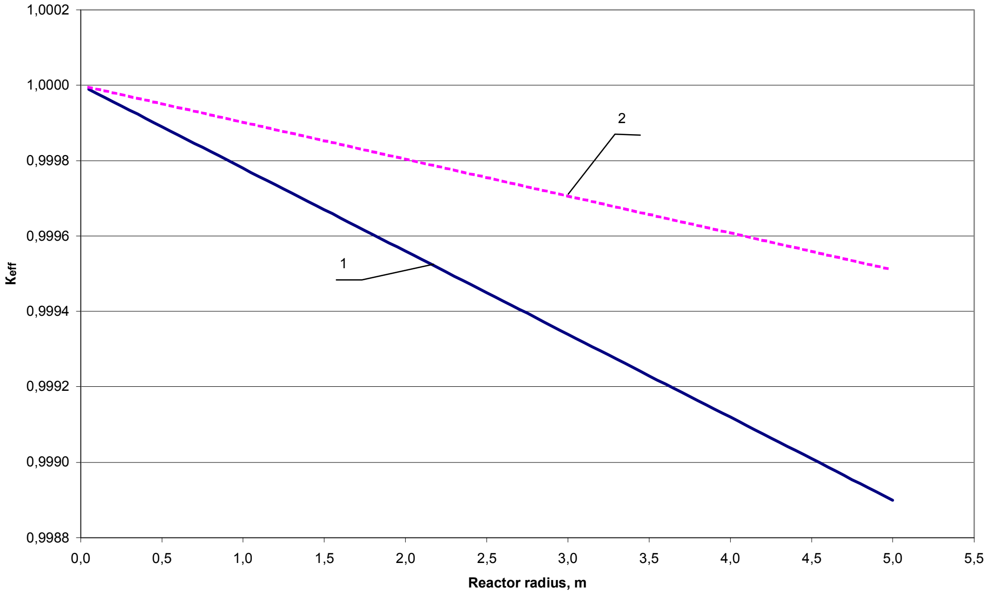

Fig.1. Dependence of Keff on reactor radius: 1 - for (n, 2n) source; 2 - for (γ, n) source;

REACTOR KINETICS

There are two sides of the problem of achieving of reactivity evaluations accuracy in nuclear reactor experiments. The first one is an adequate model idea of nuclear reactor dynamic [2,3]. The second one is a reactimeters constant providing [1,4].

If delayed neutrons are born in a reactor not only as a result of decay of fission fragments then the well known equations of reactor point kinetics with six groups of delayed neutrons [1] may be unsuitable for describing kinetics of such a reactor. Consequently, reactimeter instruments based on Inverse Solution of these Equations (ISE) may be invalid for calculation of reactivity in a reactor with additional sources of delayed neutrons.

According to [1] the heavy water reactor kinetics taking into account delayed photoneutrons can be described by the following set of equations:

$$\begin{cases} \dfrac{dn}{dt} = \dfrac{\rho_0 - \beta_{eff}}{l} n(t) + \sum\limits_{i=1}^{6} \lambda_i C_i + \sum\limits_{j=1}^{9} \lambda_j C_j \\ \dfrac{dC_i}{dt} = \dfrac{\beta_{effi}}{l} n(t) - \lambda_i C_i(t), \qquad i = 1..6 \\ \dfrac{dP_j}{dt} = \dfrac{\beta_{effj}}{l} n(t) - \lambda_{pj} P_j, \\ \dfrac{dC_j}{dt} = \lambda_{pj} P_j - \lambda_j C_j, \qquad j = 1..9 \end{cases} \tag{2}$$

where

$$\beta_{eff} = \sum_{i+1}^{6} \beta_{effi} + \sum_{j=1}^{9} \beta_{effj},$$

λ_p is the decay constant of a parent nucleus and P is the concentration of parent nuclei. All the rest symbols are of common knowledge.

On the base of equations (2) by means of standard transformations it is possible to describe the heavy water reactor point kinetics using integro-differential equation of the following type:

$$\frac{dn}{dt}=\frac{\rho-\beta_{eff}}{\Lambda}n(t)+\frac{1}{\Lambda}[\sum_{i=1}^{6}\lambda_i\beta_{effi}\int_{-\infty}^{t}e^{-\lambda_i(t-t')}n(t')dt'+ \tag{3}$$
$$+\sum_{j=1}^{9}\lambda_j\lambda_{pj}\beta_{effj}\int_{-\infty}^{t}e^{-\lambda_j(t-\tau)}\int_{-\infty}^{\tau}e^{-\lambda_{pj}(\tau-t')}n(t')dt'd\tau].$$

If one assumes that the decay of parent nuclei is fast enough for their life-time finiteness should not be taking into account ($\lambda_p=\infty$), then the equation (3) can be written in the form of:

$$\frac{dn}{dt}=\frac{\rho-\beta_{eff}}{\Lambda}n(t)+\frac{1}{\Lambda}\left[\sum_{i=1}^{6}\lambda_i\beta_{effi}\int_{-\infty}^{t}e^{-\lambda_i(t-t')}n(t')dt'+\sum_{j=1}^{9}\lambda_j\beta_{effj}\int_{-\infty}^{t}e^{-\lambda_j(t-t')}n(t')dt'\right],$$

which differs from the ordinary one only by the number of groups of delayed neutrons.

Hence the general ISE for a heavy water reactor can be given by

$$\rho=1+\frac{\Lambda}{\beta_{eff}}\frac{1}{n(t)}\frac{dn}{dt}-\frac{\sum_{i=1}^{6}\lambda_i a_i\int_{-\infty}^{t}e^{-\lambda_i(t-t')}n(t')dt'+\sum_{j=1}^{9}\lambda_j\lambda_{pj}a_j\int_{-\infty}^{t}e^{-\lambda_j(t-\tau)}\int_{-\infty}^{\tau}e^{-\lambda_{pj}(\tau-t')}n(t')dt'd\tau}{n(t)}.$$

At $\lambda_p\to\infty$

$$\rho=1+\frac{\Lambda}{\beta_{eff}}\frac{1}{n(t)}\frac{dn}{dt}-\frac{\sum_{i=1}^{6}\lambda_i a_i\int_{-\infty}^{t}e^{-\lambda_i(t-t')}n(t')dt'+\sum_{j=1}^{9}\lambda_j a_j\int_{-\infty}^{t}e^{-\lambda_j(t-t')}n(t')dt'}{n(t)}.$$

To evaluate the effect of delayed photoneutrons on reactivity measurements by a reactimeter the modeling of point kinetics of a heavy water reactor, using step

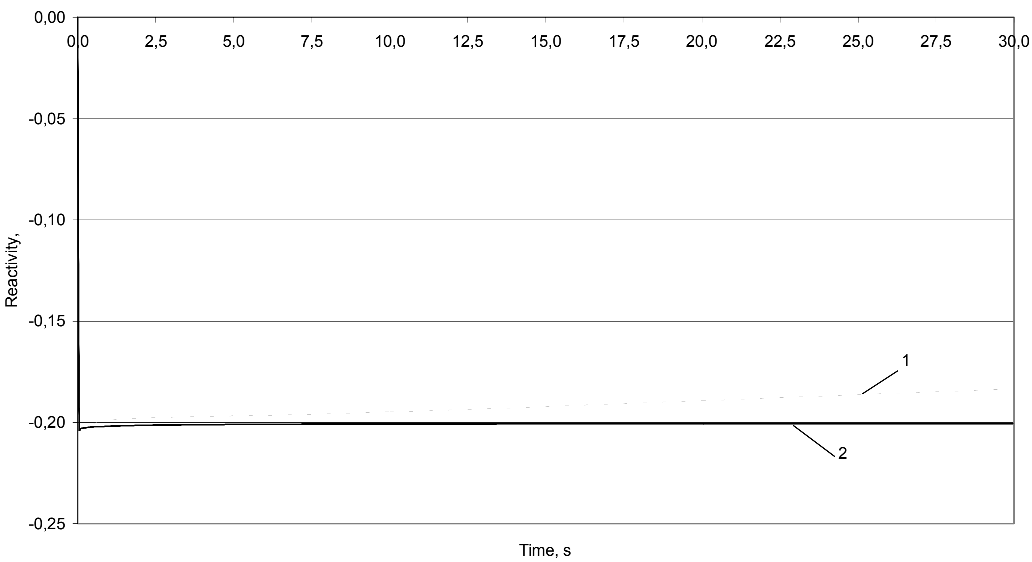

Fig.2. Comparative analysis with 6(1) and 15(2) groups of delayed neutrons(time discreteness interval $\Delta t=$ 0.05 s)

increments of negative reactivity was carried out. A general equation of inverse hours for a heavy water reactor has been derived:

$$\omega_m l = -\beta_{eff} + \rho_0 + \sum_i \beta_{effi}\lambda_i/(\omega_m + \lambda_i) + \sum_j \frac{\beta_{effi}\lambda_{pj}\lambda_j}{(\omega_m + \lambda_{pj})(\omega_m + \lambda_j)}.$$

If $\lambda_p \to \infty$, then this equation is transformed into the ordinary equation of inverse hours:

$$\omega_m l = -\beta_{eff} + \rho_0 + \sum_i \frac{\beta_{effi}\lambda_i}{(\omega_m + \lambda_i)} + \sum_j \frac{\beta_{effi}\lambda_j}{(\omega_m + \lambda_j)}. \qquad (4)$$

Reactor kinetics has been modeled by the calculation of neutron density decrease in a reactor using the formula:

$$n(t) = \sum_{m=1}^{16} N_m e^{\omega_m t},$$

where parameter N_m and ω_m are calculated using the inverse hours equation (4) with the given values l, β_{eff}, λ, ρ_0 .

There are three variants of applying digital reactimeter for analysis of neutron density decreasing in a reactor. The reactimeter has been realized using the algorithm:

$$\rho_j = 1 + \frac{\Lambda}{\beta}\alpha_j - \frac{\sum_i \lambda_i W_{ij}}{n_j}, \qquad (5)$$

where

$$W_{ij} = W_{ij-1}e^{-\lambda_i \Delta t} + \frac{a_i}{\lambda_i + \alpha_j}(n_j - n_{j-1}e^{-\lambda_i \Delta t}), \qquad \left\{ W_{ij} \equiv a_i \int_{-\infty}^{j\Delta t} e^{-\lambda_i (t-t')} n(t')dt' \right\}$$

j – time step, Δt – time discreteness interval.

Initial conditions were assumed to be

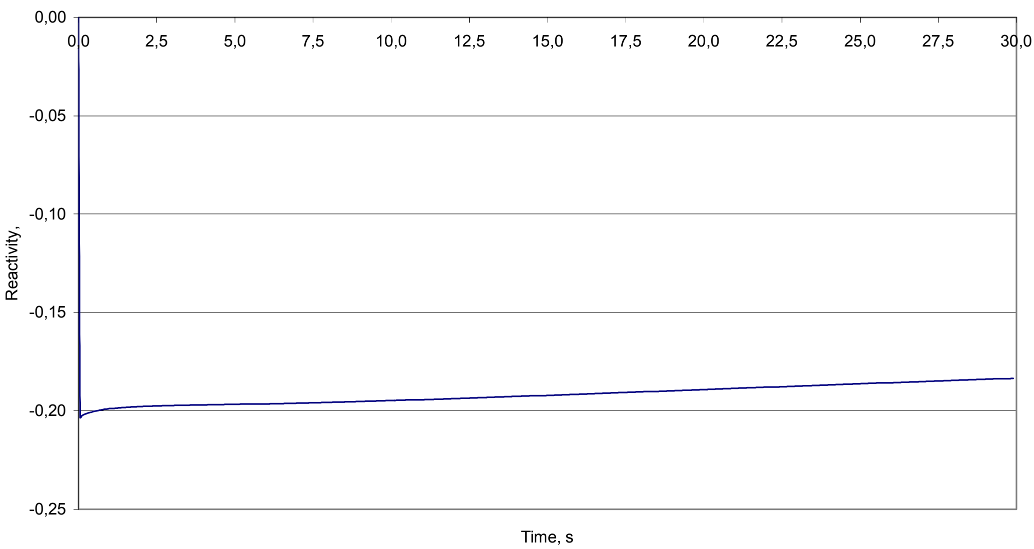

Fig.3. Reactivity with six groups of delayed neutrons with β= 0.75% (time discreteness interval Δt = 0.05 s)

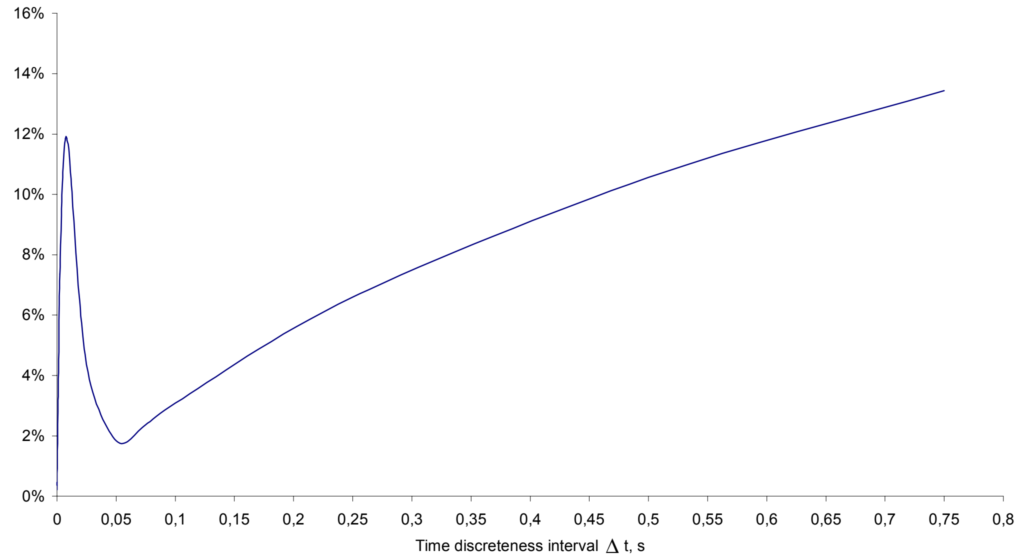

Fig. 4. Dependence of error in reactivity evaluation ρ on time discreteness interval Δt

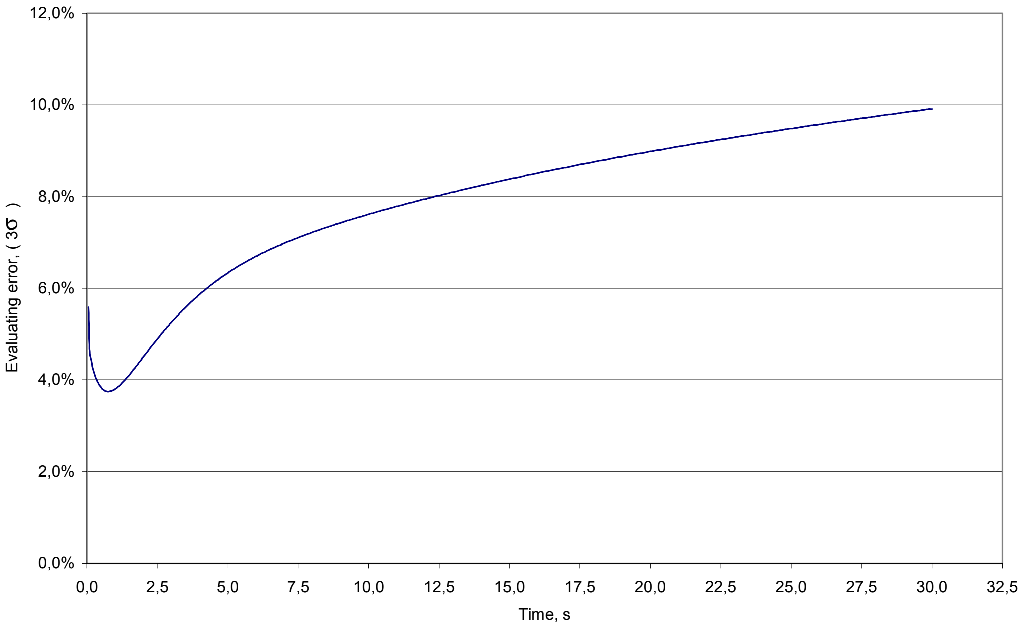

Fig. 5. Analysis of error in reactivity evaluation with difference constants of delayed neutrons within 10% (time discreteness interval Δt =0.05 s)

$$W_{i0} = a_i \int_{-\infty}^{0} n_0 e^{-\lambda_i (0-t')} dt' = \frac{a_i}{\lambda_i} n_0.$$

The mentioned three variants are as follows

- Reactimeter with ordinary six groups of delayed neutrons and effective fraction of β_{eff} = 0.65%;
- Reactimeter with ordinary six groups of delayed neutrons and effective fraction of β_{eff} = 0.75% which includes contribution of photoneutron reactions;
- Reactimeter with 15 groups of delayed neutrons (6 ordinary and 9 photoneutron) and

the effective fraction of β_{eff} = 0.75%.

Fig. 2-5 show the calculation results at $\rho_0 = -0.2\ \beta_{eff}$. It can be seen that:

- Neglect of delayed photoneutrons in the reactimeter meets with considerable errors in evaluation of the reactivity in a heavy water reactor and leads to distortion of its dynamical characteristics (see Fig.2).
- If in usual reactimeter considered delayed photoneutrons are as a correction to the fraction of delayed neutrons it will improve to some extent the reactivity estimation immediately after its jump, but dynamics characteristics will not be improved (see Fig.3).
- Specialized reactimeter realizing scheme of the equation (5) gives a good accuracy of reactivity estimations (see Fig.2). The accuracy, immediately after the jump, depends basically on time discreteness interval with which information arrives at the reactimeter input (see Fig.4).
- Difference in reactimeter constants of delayed photoneutrons from the reactor ones within 10% leads to an error in evaluating reactivity (which dynamics is shown in Fig.5) not more than 10% at any moment of time up to 30 sec after disturbance has been introduced.

CONCLUSIONS

Based on the evaluations performed the important conclusion can be drown: calculation of a heavy water reactor of practically feasible dimensions it's not necessary to take (γ, n) and (n, 2n) sources into consideration.

To analyze transient prosesses in a heavy water reactor by a reactimeter based on inverse solution of kinetics equations, a specialized reactimeter based on equation (5) with the appropriate constants is required. In this case constant uncertainties for (γ, n) reactions within 10% lead to an error in the reactivity evaluation not more than 10% up to 30 sec of time after disturbance has been introduced.

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For the last years in Russia the specific change in the ILW and LLW management has been surfaced. It is resulted in the prospective processes, equipment and installations for waste conditioning as well as for original findings based on the fundamental science, engineering and technology achievements, including progress in radiation biology.

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Evaluation and Comparison of Plutonium Potential Hazard \A.G. Aseev, S.A. Subbotin; Editorial board of journal "Izvestia visshikh uchebnikh zavedeniy. Yadernaya energetica" (Communications of Higher Schools. Nuclear Power Engineering) - Obninsk, 1999. - 9 pages, 1 table. - References, 7 titles.

An attempt to reevaluate plutonium as very toxic element was made in the article. Plutonium radiation hazard and plutonium properties dangerous for human being and the environment are considered. Estimation of its chemical toxicity also was suggeseted and it was compared with radiation plutonium toxicity. An estimation of real danger related to plutonium is represented in this article.

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FACT98 Code for Three-Dimensional Neutronics and Thermal Hydraulics Calculations of Boiling VK-300 Reactor\ S.V. Barinov, V.V. Vasil'ev, V.K. Vikulov, V.K. Davidov, A.P. Zhirnov, Yu.I. Mityaev, A.V. Radkevich, M.I. Rozhdestvensky; Editorial board of journal "Izvestia visshikh uchebnikh zavedeniy. Yadernaya energetica" (Communications of Higher Schools. Nuclear Power Engineering) - Obninsk, 1999. - 4 pages, 1 illustration. - References, 1 titles.

FACT98 code permits to calculate stationary states of a reactor, burn-up of fuel subject to overload and transposition of fuel assemblies as well power distribution, control rods displacement, reactivity effects and coefficients etc. Later is planed to add into the program calculation of the transient process on the basis of a spatial neutron dynamics and thermal hydraulics.

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Evaluation of effects of (γ,n) & (n,2n) reactions on criticality and kinetics of heavy-water reactor \ Yu.V. Volkov, T.G. Petrosov, M. Moniri; Editorial board of journal "Izvestia visshikh uchebnikh zavedeniy. Yadernaya energetica" (Communications of Higher Schools. Nuclear Power Engineering) - Obninsk, 1999. - 7 pages, 5 illustrations. - References, 4 titles.

The effect of photoneutron reactions on criticality and dynamic of a heavy water reactor has been evaluated. It has been shown that these reactions are not to be considered during neutron-physical calculations of a nuclear reactor having practically feasible dimensions. At the same time the effect of delayed photoneutron reactions on dynamics of a heavy water reactor is essential. The digital reactimeter for such reactor has been developed and tested in imitation experiment.

УДК 621.039.526

Numerical and Experimental Investigations of Stable Heat-Exchange Conditions with Liquid Metal Boiling under Fast Reactor Accident Heat Removal Regime \ A.P. Sorokin, A.D. Yefanov, Ye.F. Ivanov, D.Ye. Martsiniouk, G.P. Bogoslovskaya, K.S. Rymkevich, V.L. Malkov; Editorial board of journal "Izvestia visshikh uchebnikh zavedeniy. Yadernaya energetica" (Communications of Higher Schools. Nuclear Power Engineering) - Obninsk, 1999. - 11 pages, 8 illustrations. - References, 8 titles.

The description of test facility, sensors, measurement procedure and the experimental data on investigation of liquid metal coolant boiling in a model of fast reactor fuel subassembly under the accident heat removal conditions with small circulation rates are represented. The physics, performances and stability of various boiling regimes observed in experiments (nucleate, slug, disperse-annular) are analyzed. Experimental pattern map for liquid metal boiling was obtained. The description of a mathematical model of liquid metal boiling in the natural circulation circuit and results of test accounts for conditions with increasing of energy generation and with sharp reduction of pressure are represented.

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Development of the Chemical Treatment Methods for Thorium Materials in a Uranium - Thorium Fuel Cycle \ B.Ya. Zilberman, L.V. Sytnik, B.Ya. Galkin, A.G. Gorsky, V.B. Pavlovich, E.Ya. Smetanin, F.P. Raskach; Editorial board of journal "Izvestia visshikh uchebnikh zavedeniy. Yadernaya energetica" (Communications of Higher Schools. Nuclear Power Engineering) - Obninsk, 1999. - 7 pages, 3 illustrations, 3 tables. - References, 3 titles.