COUPLED FAST-THERMAL REACTOR SYSTEM: THEORY AND EXPERIMENT

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ABSTRACT

The mathematical model for the dynamics of coupled reactors was developed using the integral neutron kinetic model, the equations for feedback processes, and the equations for the system reactivity. The Monte Carlo method was used for calculation of parameters of this model.

The neutron physical characteristics and dynamic parameters of pulse coupled reactor system consisting of fast burst reactor and subcritical thermal module are studied in detail. The numerical simulation results were compared with experimental data. It was shown that experimental data and computed results are in a good agreement. Developed model makes it possible to simulate physical behavior of complex nuclear installations of coupled reactors with different neutron spectra and to predict all needed parameters with adequate precise.

1. INTRODUCTION

Important application of coupled reactors, which were proposed recently, are the subcritical blanket system for accelerator-driven systems and hybrid fusion-fission reactors (references 1,2), nuclear pumped lasers (reference 3). Such a system could provide the cascade multiplication of neutrons and essentially reduce the power requirements for external neutron source. Such cascade energy amplifiers have high level of inherent nuclear safety due to their deep subcriticality.

An important and challenging problem of advanced reactor physics and neutronics is theoretical and experimental investigation of fundamental processes of neutron transport, as well as the nuclear safety of systems described above. The kinetics of coupled reactor system is determined by the level of interaction between the components of the system and can substantially differ from standard reactor kinetics. In this case, special mathematical models and computer codes must be used for investigation of fundamental neutron transport processes. The kinetics of coupled system may be described mathematically in terms of the different mathematical models of coupled reactors (“point” approximation and 3D models).

In this paper, theory of coupled fast-thermal reactor system is discussed. The space-time kinetics models and criticality conditions of a system mentioned above are described. Simulation of neutronic and dynamic characteristics of a coupled reactor-laser system is produced. The results of experimental and numerical studies are compared and discussed.

2. NEUTRON KINETICS OF COUPLED REACTOR SYSTEMS

The theory of coupled reactors was founded by R. Avery more than forty years ago (reference 4). Several effective approaches to the mathematical simulation of coupled reactor kinetics have been elaborated later (references 5,6). To describe the space-time neutron transport in the coupled reactors, the integral neutron kinetics model is also proposed recently (references 7,8).

2.1 INTEGRAL NEUTRON KINETICS MODEL

Space-time distribution of the fission density $P(\vec{\mathbf{r}},t)$ in the multiplicative neutron medium V may be described using the integral transport equation (references 7,8):

$$P(\vec{\mathbf{r}},t)=\int_0^t\int_V \alpha(\vec{\mathbf{r}},\vec{\mathbf{r}}',t,\tau)P(\vec{\mathbf{r}}',\tau)d\vec{\mathbf{r}}'d\tau+\int_0^t\int_V \alpha^s(\vec{\mathbf{r}},\vec{\mathbf{r}}',t,\tau)Q(\vec{\mathbf{r}}',\tau)d\vec{\mathbf{r}}'d\tau . \qquad (1)$$

Here: $\alpha(\vec{\mathbf{r}},\vec{\mathbf{r}}',t,\tau)$ is the space-time distribution of “secondary” fissions at the point with coordinate $\vec{\mathbf{r}}$ and at time moment t, produced by “initial” fission in the point with coordinate $\vec{\mathbf{r}}'$ and time moment τ. The function $\alpha^s(\vec{\mathbf{r}},\vec{\mathbf{r}}',t,\tau)$ has the same meaning for fissions from external source with intensity $Q(\vec{\mathbf{r}}',\tau)$.

The particular case of model (1) is multi-core approximation (references 8,9), where the function $P(\vec{\mathbf{r}},t)$ can be presented as following expression:

$$P(\vec{\mathbf{r}},t)=N_i(t)\cdot\varphi_i(\vec{\mathbf{r}}),\ \vec{\mathbf{r}}\in V_i,\ V=\sum_{i=1}^{m}V_i . \qquad (2)$$

In this case, the model (1) may be written in the form

$$N_i(t)=\sum_{j=1}^{m}\left\{\int_{-\infty}^{t}\alpha_{ij}(t-\tau)N_j(\tau)\,d\tau+\int_{-\infty}^{t}\alpha_{ij}^{s}(t-\tau)S_j(\tau)\,d\tau\right\},\ i=\overline{1,m} . \qquad (3)$$

Here: *i* is core number in coupled system; $N_i(t)$ is time-dependent fission density in the core *i*; $\alpha_{ij}(\tau)$ is the time distribution of the neutrons from “first” fissions in core *i* per one fission neutron transported from core *j*; α_{ij}^{s} is analogous function for fission’s neutron density from external source with output $S(t)$.

Thus, $\alpha_{ij}(\tau)$ and $\alpha_{ij}^{s}(\tau)$ in the model (3) are completely described the processes of neutron transport between the components of the coupled system. The Monte-Carlo method (MCM) may be used for calculation of such a parameters. MCNP code (reference 12) was modified for this purpose using estimation $\nu\Sigma_f(\vec{\mathbf{r}},E)/\Sigma_t(\vec{\mathbf{r}},E)$ on each neutron collision in *i*-th core from source neutrons in *j*-th zone with space distribution $\varphi_j(\vec{\mathbf{r}})$ (see system (2)) and prompt time distribution (reference 11).

In practice, $\alpha_{ij}(\tau)$ and $\alpha^{s}_{ij}(\tau)$ functions may be approximated by sets of exponents

$$\alpha_{ij}(\tau)=k^{ef}_{ii}(\tau)\left\{(1-\beta_j)\sum_{p=1}^{m_{ij}}\frac{k^p_{ij}}{\ell^p_{ij}\sum_p k^p_{ii}}e^{-\frac{\tau}{\ell^p_{ij}}}+\frac{\sum_{p=1}^{m_{ij}}k^p_{ij}}{\sum_p k^p_{ii}}\sum_{q=1}^{D_j}\lambda^q_j\beta^q_j e^{-\lambda^q_j\tau}\right\}. \quad (4)$$

$$\alpha^{s}_{ij}(\tau)=k^{ef}_{ii}(\tau)\sum_{r=1}^{m^s_{ij}}\frac{k^r_{sij}}{\ell^r_{sij}\sum_r k^r_{ii}}e^{-\frac{\tau}{\ell^r_{sij}}}$$

Here: k^{ef}_{ii} is multiplication factor for core *i*; k^p_{ij}, ℓ^p_{ij}, k^r_{sij} and ℓ^r_{sij} are approximation parameters for prompt neutrons (m_{ij} and m^s_{ij} are the numbers of exponents); β, β_q and λ_q are parameters of the delayed neutrons (D is the number of delayed neutron groups).
In this case, parameters k^p_{ij} and ℓ^p_{ij} of equation (3) have a simple physical sense:

$$\int_0^\infty \alpha_{ij}(\tau)d\tau=\sum_{p=1}^{m_{ij}}k^p_{ij}=\mathrm{k}_{ij} \text{ and } \frac{\int_0^\infty \alpha_{ij}(\tau)\tau d\tau}{\int_0^\infty \alpha_{ij}(\tau)d\tau}=\frac{\sum_{p=1}^{m_{ij}}k^p_{ij}\ell^p_{ij}}{\sum_{p=1}^{m_{ij}}k^p_{ij}}=\mathrm{l}_{ij}. \quad (5)$$

Here: k_{ij} and l_{ij} are analog of coefficients of neutron coupling between cores *i* and *j* and lifetimes, respectively, determined in R. Avery theory (reference 4).
Using the integral kinetics model (3),(4) the value of multiplication factor of whole coupled system, k_{sys}, may be obtained as solution of following algebraic equation

$$\det\begin{vmatrix} k^{ef}_{11}-k_{sys} & k^{ef}_{11}\frac{\sum_{p=1}^{m_{12}}k^p_{12}}{\sum_{p=1}^{m_{11}}k^p_{11}} & \cdots & k^{ef}_{11}\frac{\sum_{p=1}^{m_{1m}}k^p_{1m}}{\sum_{p=1}^{m_{11}}k^p_{11}} \\ \vdots & \vdots & \vdots & \vdots \\ k^{ef}_{mm}\frac{\sum_{p=1}^{m_{m1}}k^p_{m1}}{\sum_{p=1}^{m_{mm}}k^p_{mm}} & k^{ef}_{mm}\frac{\sum_{p=1}^{m_{m2}}k^p_{m2}}{\sum_{p=1}^{m_{mm}}k^p_{mm}} & \cdots & k^{ef}_{mm}-k_{sys} \end{vmatrix}=0. \quad (6)$$

As the sample, the results of the MCM computation of $\alpha_{ij}(\tau)$ function with exponential approximation are shown in figure 1 (reference 8).

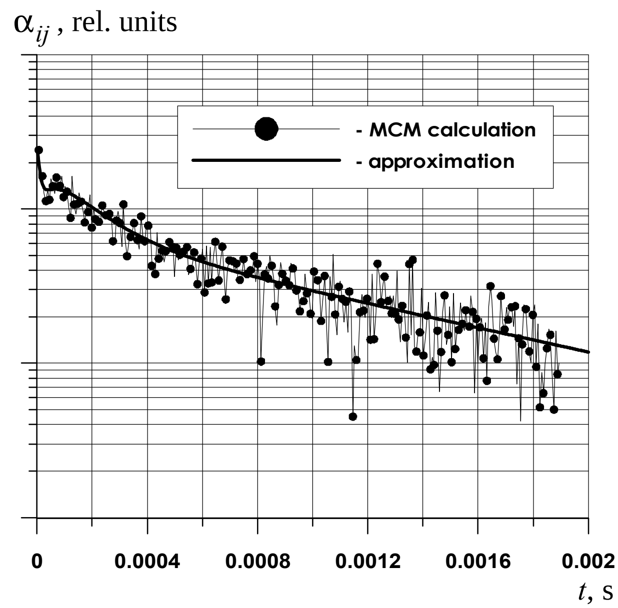


Figure 1. Time behavior of the function α_{ij}.

2.2 MODIFIED INTEGRAL NEUTRON KINETICS MODEL

In order to use the neutron kinetics model (3),(4) in practice for real complex system, we must calculate too many parameters, such as functions $\alpha_{ij}(\tau)$ and $\alpha_{ij}^{s}(\tau)$. The total computational time costs in this case may be huge. For particular case of the coupled reactor system, consisting of fast reactor and subcritical module, special modification of the integral kinetics model (1) has been formulated (references 10,11). This mathematical model may be written in the following form (for simplicity we will assume that no any external neutron sources exists in subcritical module)

$$\begin{cases} N_r(t) = \int\limits_{-\infty}^{t} \left[\alpha_{rr}(t-\tau) + \alpha_{rb}(t-\tau)\right] N_r(\tau)\, d\tau + \\ \qquad + \int\limits_{-\infty}^{t} \left[\alpha_{rr}^{s}(t-\tau) + \alpha_{rb}^{s}(t-\tau)\right] S_r(\tau)\, d\tau \\ N_b(\vec{\mathbf{r}},t) = \int\limits_{-\infty}^{t} G_{br}(\vec{\mathbf{r}},t-\tau) N_r(\tau)\, d\tau + \int\limits_{-\infty}^{t} G_{bs}(\vec{\mathbf{r}},t-\tau) S_r(\tau)\, d\tau \end{cases} \quad . \qquad (7)$$

Here: $N_r(t)$ is time-dependent fission density in the fast reactor; $N_b(\vec{\mathbf{r}},t)$ is space-time distribution of fission density in subcritical module; $\alpha_{rr}(\tau)$ is a distribution of "secondary" fissions, produced in fast reactor by neutrons from the "initial" fission in the same reactor; $\alpha_{rr}^{s}(\tau)$ is analogous function for fissions produced in fast reactor by neutrons from external source with output $S_r(t)$; $\alpha_{rb}(\tau)$ is the function of "secondary" fissions in the reactor, which were produced by neutrons from fissions in the subcritical module, if the first fission also had occurred in the fast reactor; $\alpha_{rb}^{s}(\tau)$ is analogous function for external source;

$G_{br}(\vec{\mathbf{r}},\tau)$ is a total number of fissions at the point in subcritical module with coordinate $\vec{\mathbf{r}}$ and at time moment τ per one "initial" fission in fast reactor; $G_{bs}(\vec{\mathbf{r}},\tau)$ is analogous function for external source. The kernels $G_{br}(\vec{\mathbf{r}},\tau)$ and $G_{bs}(\vec{\mathbf{r}},\tau)$ are the components of the Green's function for the described system.

In practical calculations, the parameters of model (7) may be approximated by set of exponents (multi-zone approximation of the subcritical module):

$$\alpha_{rr}(t-\tau)=\frac{k_{rr}^{ef}(t)}{\sum\limits_{p'}k_{rr}^{p'}}\sum_{p=1}^{m_{rr}}k_{rr}^{p}\left[\frac{(1\text{-}\beta_r)}{\ell_{rr}^{p}}\cdot e^{-\frac{t-\tau}{\ell_{rr}^{p}}}+\sum_{q=1}^{D_r}\lambda_r^q\beta_r^q e^{-\lambda_r^q(t-\tau)}\right];$$

$$\alpha_{rb}(t-\tau)=\frac{k_{rr}^{ef}(t)}{\sum\limits_{p'}k_{rr}^{p'}}\sum_{p=1}^{m_{rb}}k_{rb}^{p}\left[\frac{(1\text{-}\beta_r)}{\ell_{rb}^{p}}\cdot e^{-\frac{t-\tau}{\ell_{rb}^{p}}}+\sum_{q=1}^{D_r}\lambda_r^q\beta_r^q e^{-\lambda_r^q(t-\tau)}\right]; \qquad (8)$$

$$\alpha_{rr}^{s}(t\text{-}\tau)=\frac{k_{rr}^{ef}(t)}{\sum\limits_{p'}k_{rr}^{p'}}\sum_{p=1}^{m_{sr}}\frac{k_{sr}^{p}}{\ell_{sr}^{p}}\cdot e^{-\frac{t\text{-}\tau}{\ell_{sr}^{p}}};\ \alpha_{rb}^{s}(t-\tau)=\frac{k_{rr}^{ef}(t)}{\sum\limits_{p'}k_{rr}^{p'}}\sum_{p=1}^{m_{sb}}\frac{k_{sb}^{p}}{\ell_{sb}^{p}}\cdot e^{-\frac{t-\tau}{\ell_{sb}^{p}}};$$

$$G_{br}^{i}(t-\tau)=\sum_{p=1}^{m_{br}^{i}}\frac{k_{br_i}^{p}}{\ell_{br_i}^{p}}\cdot e^{-\frac{t\text{-}\hat{o}}{\ell_{br_i}^{p}}};\ G_{bs}^{i}(t-\tau)=\sum_{p=1}^{m_{bs}^{i}}\frac{k_{bs_i}^{p}}{\ell_{bs_i}^{p}}\cdot e^{-\frac{t-\tau}{\ell_{bs_i}^{p}}};\ i=\overline{1,B}.$$

Here: $k_{rr}^{ef}(t)$ is multiplication factor of fast reactor, B is number of zones in the subcritical module.

It is important to note that the direct dependence exists between modified the model (7),(8) and two-zone integral model (3),(4) parameters:

$$\mathrm{k}_{21}\frac{1}{1\text{-}\mathrm{k}_{22}}=\int_0^\infty G_{br}(\tau)d\tau;\ \mathrm{k}_{21}\frac{1}{1-\mathrm{k}_{22}}\mathrm{k}_{12}=\int_0^\infty \alpha_{rb}(\tau)d\tau;$$

$$\mathrm{k}_{12}=\int_0^\infty \alpha_{rb}(\tau)d\tau\Big/\int_0^\infty G_{rb}(\tau)d\tau, \qquad (9)$$

where indexes "1" and "2" mean reactor and subcritical module, respectively.

The value of multiplication factor of whole coupled system "fast reactor – subcritical module", k_{sys}, may be obtained as the solution of following equation:

$$k_{rr}^{ef}+k_{rr}^{ef}\frac{\sum\limits_{p'=1}^{m_{rb}}k_{rb}^{p'}}{\sum\limits_{p'=1}^{m_{rr}}k_{rr}^{p'}}-k_{sys}=0. \qquad (10)$$

To calculate the model (7) parameters, we used the same algorithm as for model (3) described above. It was also realized in the MCNP code (reference 12). As the sample, the MCM computation results of the $\alpha_{rr}(\tau)$, $\alpha_{rb}(\tau)$ and $G_{br}(\tau)$ functions and their approximations by exponential sets are shown on figures 2-4 (references 10,11).

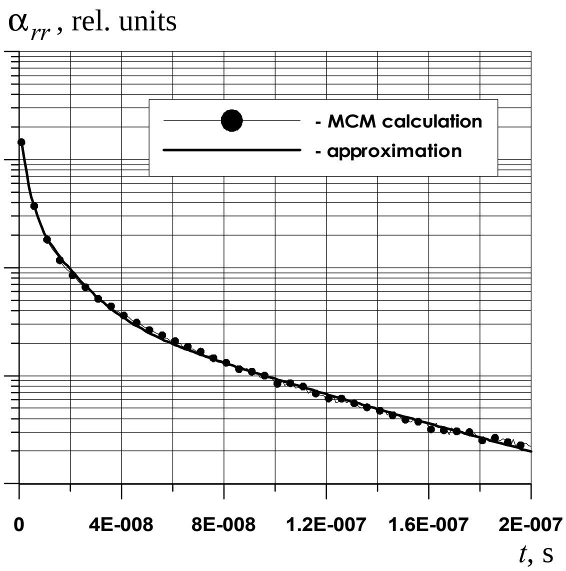


Figure 2. Time distribution of α_{rr}.

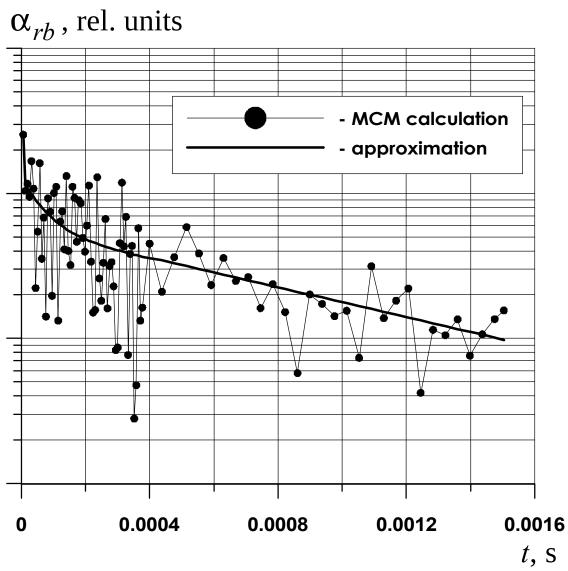


Figure 3. Time distribution of α_{rb}.

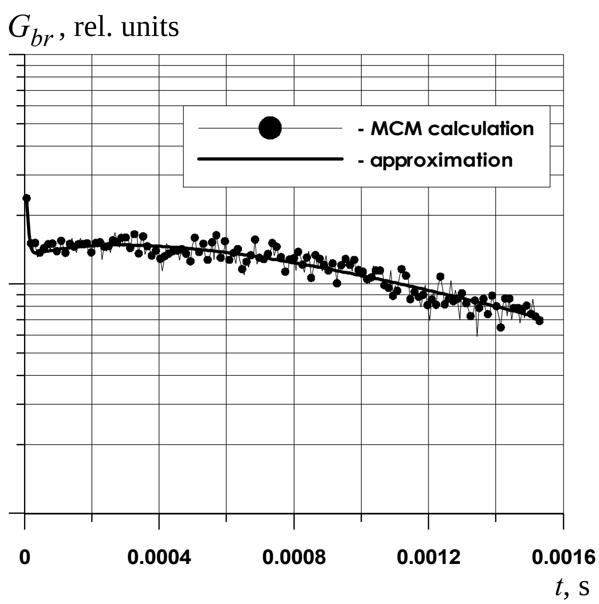


Figure 4. Time distribution of G_{br}.

It is important to note that the modified integral kinetics model was tested on the non-stationary experiments at the Universal Critical Facility (IPPE, Obninsk) which is a “zero-power” critical assembly of coupled fast-thermal reactor system (reference 11).

One of the main problem of correct using of the neutron kinetics models (3) and (7) is the determination of time-dependent multiplication factor of core i $k_{ii}^{ef}(t)$ or multiplication factor of fast reactor $k_{rr}^{ef}(t)$. In general case, it may be described as follows (references 9,13):

$$k_{ii}^{ef}(t) = k_i^0 + \sum_{j=1}^{M} \Delta k_{ij}^T (T_j) + \Delta k_i^N (N_i) + \Delta k_i (t), \tag{11}$$

where k_i^0 is initial multiplication factor of core i; $\Delta k_{ij}^T (T_j)$ is temperature dependent multiplication factor of j-th temperature element in i-th core; $\Delta k_i^N (N_i)$ is the change of the multiplication factor as a function of fission density in i-th core; $\Delta k_i (t)$ is the change of multiplication factor induced by the movement of the control rods.

All mathematical models described above were realized in computer codes STIK and GRIF (references 13,16,17).

3. NEUTRONICS AND DYNAMICS OF COUPLED FAST-THERMAL REACTOR SYSTEM

Theory described above we used to study the neutronics and dynamics of coupled system consisting of fast reactor and thermal subcritical module – Set “B”. This facility was constructed at the Institute for Physics and Power Engineering (Obninsk, Russia) as the energy model of high power nuclear pumped laser system (references 14,15).

3.1 CONCEPT DESCRIPTION AND PRINCIPLE OF OPERATION

Experimental system of the Set “B” consists of two main parts: reactor module and subcritical module (SM) (see figure 5).

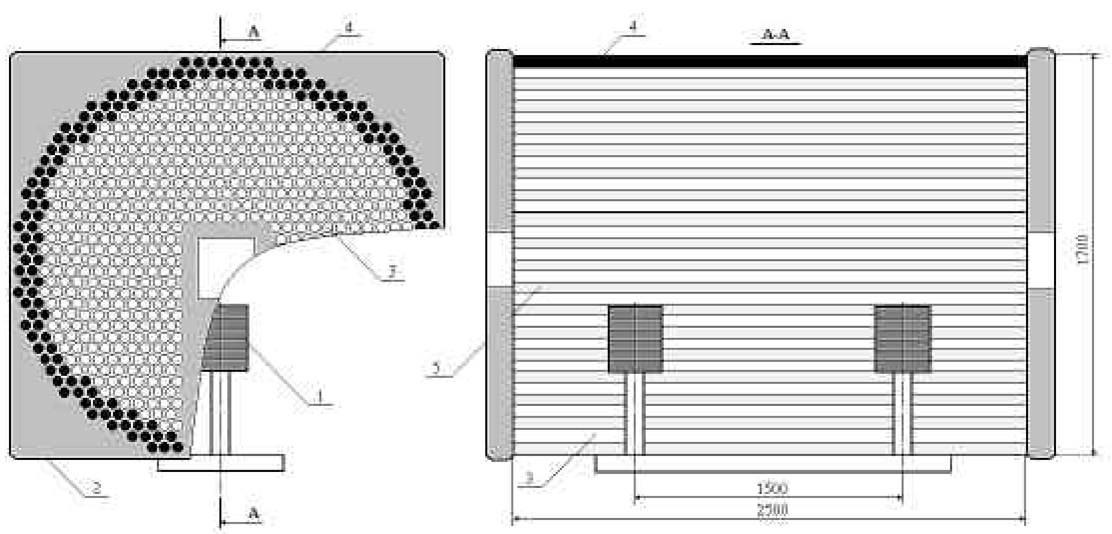
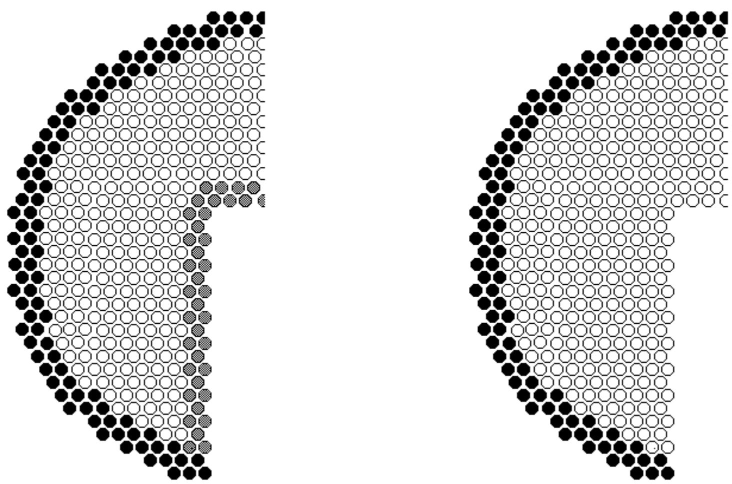


Figure 5. The scheme of reactor system of the Set “B”.

A twin-core fast burst reactor “Bars-6” (1) is used as the reactor module. The reactor parameters are as follows: dimensions of active cores - 220x220 mm; distance between cores - 1500 mm; number of fissions in two cores during the pulse - $5\cdot10^{17}$; pulse duration - 40 μs. The reactor includes a safety block, three systems of reactivity regulators and a fast control rod that, at its maximum speed, limits of reactivity insertion to 220 $/s.
The subcritical module (2) is a cylindrical structure sized to provide the space required for housing the two cores of reactor module and the other components of the system. The diameter of subcritical module is 1700 mm, and the length is 2500 mm. The SM consists of the imitators (3) and neutron moderator elements (5). The subcritical module is surrounded by the two rows of neutron reflector elements (4). The imitator consists of two thin-wall aluminum tubes concentrically arranged to provide an annulus which is filled with uranium-235 dioxide. The external reflector consists of a thin-wall stainless tube with polyethylene. If required, the subcritical module could be provided with an internal “moderator wall” (reflector) (see figure 6a).



a b

Figure 6. 1/2 of the subcritical module cross-section view from front side:
with elements of internal (a) and no internal reflector (b).

The coupled reactor system of the Set “B” operates as follows. The reactivity of the whole system increases over the prompt criticality level with high speed by extracting the fast control rod from the reactor core. Neutrons from the reactor, passing through the SM, induce a chain fission reaction of uranium-235 in the coating of imitators. So, the coupled system operates in the mode of high level neutron pulses.

3.2 NEUTRONICS ANALYSIS

The integral kinetics model (3) for the stationary state may be written in the form

$$\begin{cases}(\mathrm{k}_{rr}-1)N_r+\mathrm{k}_{rb}N_b+S_r=0\\(\mathrm{k}_{bb}-1)N_b+\mathrm{k}_{br}N_r=0\end{cases}, \qquad (12)$$

where indexes “*r*” and “*b*” mean reactor and subcritical module, respectively; N_r and N_b - power of reactor and SM, respectively; k_{ij} - coefficients of neutron coupling between system components (see formulas (5)).

We can obtain:

$$\mathrm{k}_{br} = (1-\mathrm{k}_{bb})\frac{N_b}{N_r};\ \mathrm{k}_{rb} = (1-\mathrm{k}_{rr})\frac{N_r}{N_b} - \frac{S_r}{N_b}. \quad (13)$$

Assume that $S_r << N_r$, reactivity of reactor may be estimated as the solution of following equation (see formulas (9),(10))

$$1-\mathrm{k}_r \approx \frac{\mathrm{k}_{br}\mathrm{k}_{rb}}{1-\mathrm{k}_{bb}} = \int_0^\infty \alpha_{rb}(\tau)d\tau = \Delta k_{rb}^{act}, \quad (14)$$

where Δk_{rb}^{act} is the reactor reactivity perturbation by fission neutrons of the subcritical module – so-called "active" component of the reactor induced reactivity.
We can defined the coefficient of neutron coupling k_{rb}:

$$k_{rb} \approx \Delta k_{rb}^{act}\frac{N_r}{N_b}. \quad (15)$$

The dependencies $\rho_{rr}(\mathrm{k}_{bb})$ ($\rho_{rr} = \frac{\mathrm{k}_{rr}-1}{\mathrm{k}_{rr}}$) under criticality condition of coupled system ($k_{sys}=1$) may be obtained using formulas (13)-(15). Such curves are shown in figure 7 ($\tilde{\mathrm{k}} = \mathrm{k}_{rb}\mathrm{k}_{br}$) where the real conditions of the Set "B" reactor system for two variants of SM (with elements of internal reflector and without it) are used.

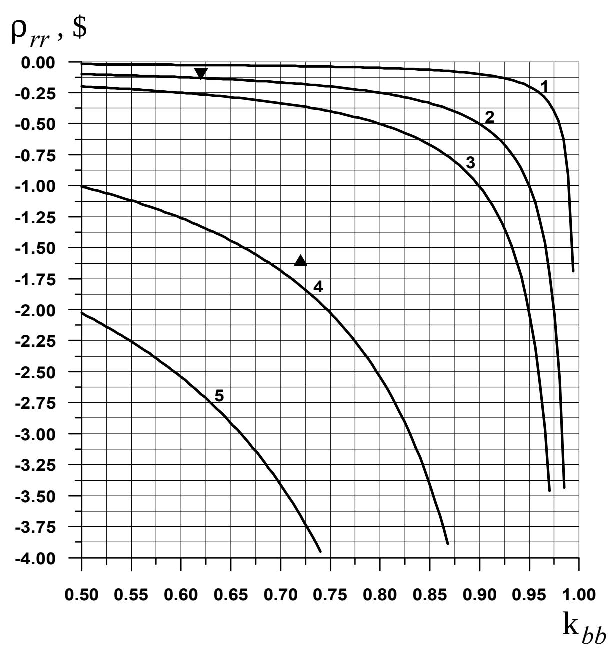


Figure 7. Criticality conditions for coupled system "fast reactor – subcritical module"
(▼ - SM with internal reflector; ▲ - no internal reflector):
1 - $\tilde{\mathrm{k}}$ =0.01\$; 2 - $\tilde{\mathrm{k}}$ =0.05\$; 3 - $\tilde{\mathrm{k}}$ =0.1\$; 4 - $\tilde{\mathrm{k}}$ =0.5\$; 5 - $\tilde{\mathrm{k}}$ =1.\$.

It is important to note that the value (see system (7))

$$\Delta k_{rb}^{pas} = \int_0^\infty \alpha_{rr}^{\text{Bars6+LM}}(\tau)d\tau - \int_0^\infty \alpha_{rr}^{\text{Bars6}}(\tau)d\tau$$

is the reactor reactivity perturbation by neutrons reflected from subcritical module (no fissions in SM) – so-called "passive" component of the reactor induced reactivity.

Parameter

$$\ell_r = \int_0^\infty \alpha_{rr}^{\text{Bars6+LM}}(\tau)\tau d\tau \Big/ \int_0^\infty \alpha_{rr}^{\text{Bars6+LM}}(\tau)d\tau$$

is the average prompt neutron lifetime in the fast reactor.

The calculation and experimental data of neutron characteristics of the Set "B" are presented in table 1. The calculations were performed using MCNP code (reference 12).

Table 1. Neutron parameters over coupled system

Parameter	Value	
	calculation	experiment
with internal reflector		
ℓ_r, s	$1.5 \cdot 10^{-8}$	-
k_{bb}	0.69±0.01	0.66±0.02
Δk_{rb}^{pas}, $	2.01±0.02	1.90±0.03
Δk_{rb}^{act}, $	0.25±0.02	0.1±0.2
$\int_0^\infty G_{br}(\tau)d\tau$	0.24±0.01	0.22±0.03
no internal reflector		
ℓ_r, ñ	$2.0 \cdot 10^{-8}$	-
k_{bb}	0.73±0.01	0.72±0.02
Δk_{rb}^{pas}, $	1.32±0.02	1.1±0.02
Δk_{rb}^{act}, $	1.51±0.02	1.60±0.03
$\int_0^\infty G_{br}(\tau)d\tau$	0.57±0.02	0.62±0.09

It is possible to evaluate the multiplication factor of neutrons (k_{sys}) of whole system "twin-core fast burst reactor – subcritical module" as the maximum root of the following algebraic equation (see also formula (10) and reference 15)

$$\det\begin{vmatrix} k_1^{ef} + \Delta k_{rb}^{act} - k_{sys} & k_{12}^{rr} + k_{12}^{rb} \\ k_{21}^{rr} + k_{21}^{rb} & k_2^{ef} + \Delta k_{rb}^{act} - k_{sys} \end{vmatrix} = 0. \tag{16}$$

Here: k_i^{ef} is multiplication factor of core 1 and 2, respectively; k_{ij}^{rr} and k_{ij}^{rb} are coefficient of neutron coupling between reactor cores:

$$k_{ij}^{rr} = \int_0^\infty \alpha_{rr}^{ij}(\tau)d\tau; \; k_{ij}^{rb} = \int_0^\infty \alpha_{rb}^{ij}(\tau)d\tau.$$

The dependencies of $\rho_1(\rho_2)$ for the system "reactor Bars-6 + SM" were calculated using the formula (16) and the data from table 1 (see figure 8). Here: $\rho_i = \left(k_i^{ef} - 1\right) / k_i^{ef}$.

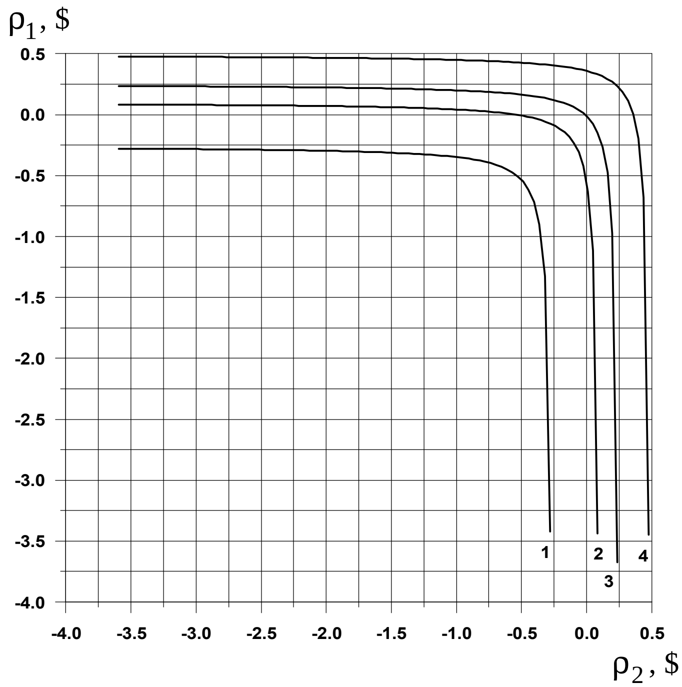


Figure 8. ρ_2 as a function ρ_1 (SM with internal reflector):
1 - ρ_{sys} =0; 2 - ρ_{sys} =0.15$; 3 - ρ_{sys} =1.$; 4 - ρ_{sys} =1.15$ (nominal pulse mode).

3.3 DYNAMICS OF THE SYSTEM

The advanced model for calculation of k_i^{ef} was proposed in previous publication (see reference 15). In these paper we used adapted model for reactor reactivity feedback estimation:

$$k_i^{ef}(t) = k_i^{cr}(t) - A_i \int_0^t N_r^i(\tau)d\tau, \qquad (17)$$

where $k_i^{cr}(t)$ is "external" reactivity input in *i*-th reactor core by fast control rods; A_i is full quasi static feedback reactivity coefficient for the *i*-th core (A_i =0.7·10^{-9} 1/J); N_r^i is power of *i*-th reactor core.

The power pulses were simulated for the coupled system "reactor + SM" using modified integral kinetics model (7) and GRIF code (reference 13,17) assuming that the reactivity input into two cores is simultaneous and at the same input rate. The parameters of the transient processes were calculated for various reactivity input rates into the two cores below the value of the delay time for shut down the safety block (Δ_{sd}). The power pulses were initiated from the power level $N_r^1(0) = N_r^2(0)$ ~1W.

The parameter $k_i^{cr}(t)$ of feedback reactivity model (17) is estimated as follows:

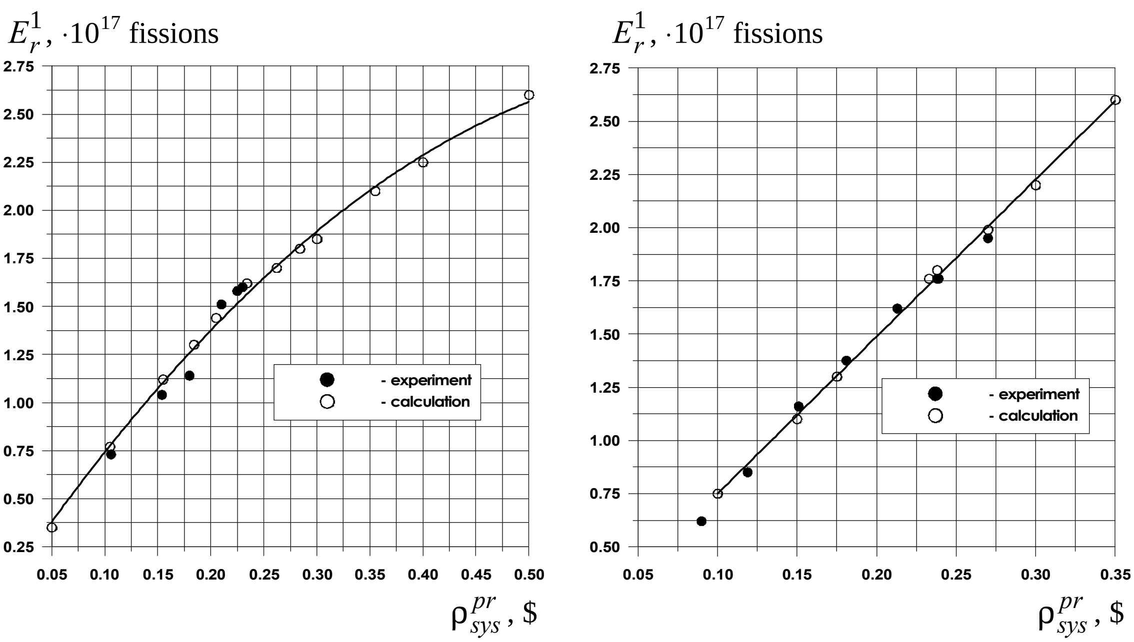
$$k_i^{cr}(t) = k_i^0 + \gamma_i t\,,\ t \le \tau_{inp}\,;$$

$$k_i^{cr}(t) = k_i^0 + \gamma_i \tau_{inp}\,,\ \tau_{inp} < t \le \tau_{inp} + \Delta_{sd}\,;$$

$$k_i^{cr}(t) = k_i^0 + \gamma_i \tau_{inp} - \gamma_{sd} \cdot \big(t - (\tau_{inp} + \Delta_{sd})\big),\ \tau_{inp} + \Delta_{sd} < t\,.$$

Here: γ_i is value of reactivity input into the reactor core; τ_{inp} is time of reactivity input; γ_{sd} is speed of reactivity input into the reactor by safety block.

The energy released in the core, E_r^1, (experimental and computational data) versus a value of the system prompt neutron reactivity is shown in figure 9 ($\rho_{sys}^{pr} = \rho_{sys}$ -1\$; $E_r^1 = \int_0^\infty N_r^1(\tau)d\tau$).



a b

Figure 9. Dependence of the energy released in the core versus the system reactivity:
a - SM with internal reflector; b - no internal reflector.

It is clear that the energy released in the reactor core for the system with internal reflector depends considerably on the reactivity input rate into the core (nonlinear dependence of energy from reactivity level). This is because of the system with internal moderator wall has a “weak” neutron coupling, and, therefore, the physical characteristics of the pulses for such a system are similar to those of a reactor without a SM (references 9,14).

The calculation of nominal power pulses (6MJ energy in one reactor core) are shown in figure 10 for a subcritical module: 1) with internal reflector (Δ_{sd} =30 ms) and 2) without it (Δ_{sd} =100 ms); γ_i =100 \$/s.
It is obvious that for the first case the pulse duration ten times less than in the second case - ~1 ms and ~10 ms, respectively, but at the same time the energy release in the subcritical module for the second case (~7 MJ) is greater than in the first case (~ 3 MJ). So, it is shown that pulse parameters of coupled system depends on the neutron coupling between components.

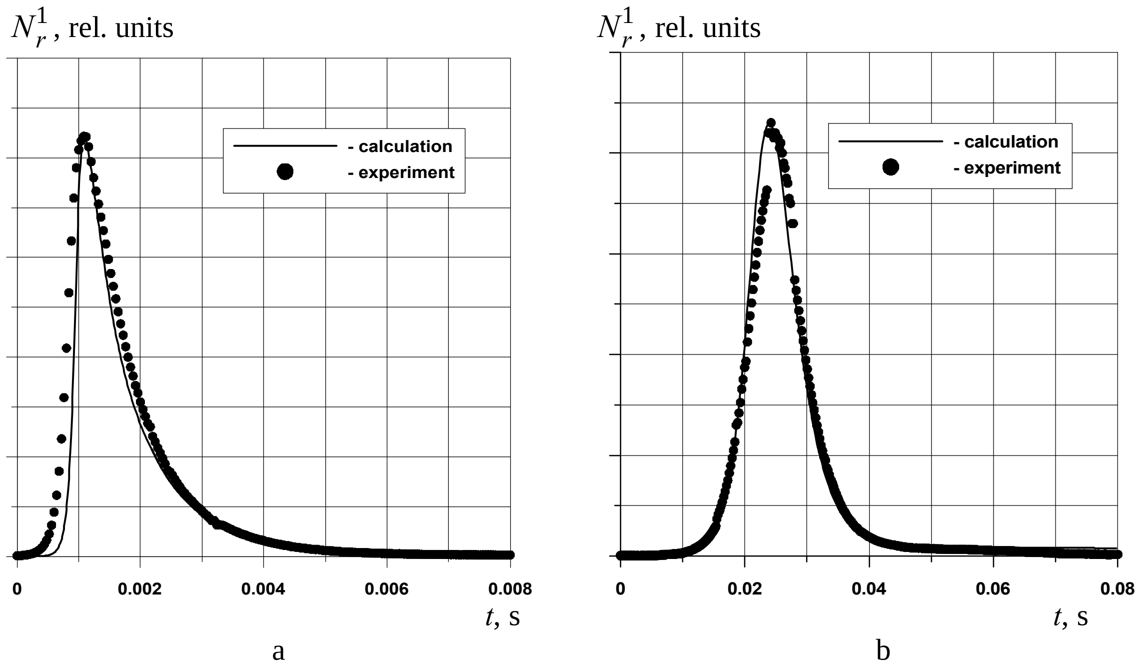


Figure 10. Reactor core power for nominal pulses:
a - SM with internal moderator wall; b - no internal moderator wall.

CONCLUSIONS

A theory and mathematical models for investigation of the space-time neutron kinetics of coupled reactors, neutronics and safety analyses of such a systems have been proposed. These models may be considered as the basis for dynamic investigations of multi-core reactor systems, especially, for fast-thermal coupled reactors. Note that Monte-Carlo techniques may be effectively used for calculation of the parameters of these models.
Neutronics and dynamics of coupled fast-thermal reactor system that consists of fast twin-core burst reactor and subcritical module are studied in detail for two variants of the subcritical module constructions (several neutron connection between system components). For such system the critical conditions are obtained using a mathematical formalism of coupled reactor theory.

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REFERENCES

1. A.P. Barzilov, A.V. Gulevich, O.F. Kukharchuk, et al., "Concept of a Coupled Blanket System for the Hybrid Fission-Fusion Reactor," in IEEE/NPSS 16th Symposium Fusion Engineering (SOFE'95), eds. G.H. Miley and C.M. Elliott, IEEE, Pescataway, NJ (1996).

2. A. P. Barzilov, A.V. Gulevich, O.F. Kukharchuk, et. al., "Neutronics Analysis for a Coupled Blanket System of the Hybrid Fission-Fusion Reactor," Obninsk, IPPE #2522 (1996).

3. P.P. Dyachenko, et al., *Fusion Technology*, **20**, 969 (1991).

4. R. Avery, "Theory of Coupled Reactors," in Proc. of 2nd Int. Conf. on Peaceful Uses of Atomic Energy, Report #1858 (1958).

5. A. Bellini-Morante, Nucleonik, **8**, 5 (1966).

6. V.F. Kolesov, et al., "Kinetics of a System of Coupled Pulse Reactors," *Atomnaya energiya*, **39**, 6 (1975), (*in Russian*).

7. S.V. Poupko, "Model of Space Kinetics of Reactor," Obninsk, IPPE #2054 (1989), (*in Russian*).

8. A.V. Gulevich, O.F. Kukharchuk, et al., "Application of the Integral Kinetic Model to Computation of the Multi-Core Multiplicative System," Obninsk, IPPE #2129 (1990), (*in Russian*).

9. O.F. Kukharchuk, and A.V. Gulevich, "Mathematical Simulation of the Coupled Reactor System Dynamics," in Proc. of Int. Conf. on Mathematics and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications (M&C-99), Madrid, Spain (1999).

10. A.V. Gulevich, O.F. Kukharchuk, et al., "Modified Neutron Kinetic Model of the Reactor-Laser System," Obninsk, IPPE #2264 (1992), (*in Russian*).

11. A.V. Gulevich, O.F. Kukharchuk, and A.P. Barzilov, "Modification of the Integral Kinetic Model for the Fast Burst Reactor with Subcritical Module," in Proc. of Int. Conf. on Mathematics and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications (M&C-99), Madrid, Spain (1999).

12. "MCNP-a General Monte Carlo Code for Neutron and Photon Transport," ed. by Briesmeister J., LANL LA-7396-M, Rev.2 (1986).

13. A.V. Gulevich, B.V. Kachanov, O.F. Kukharchuk, "Mathematical Models and Computer Cods for Investigations of Dynamics Characteristics of the Nuclear Pumped Laser Systeme," Obninsk, IPPE #2454 (1995) (*in Russian*).

14. P.P. Dyachemko, "Nuclear-Laser Power Engineering as a Prospective Direction in Nuclear Energy Utilization," in Proc. of 8th Int. Conf. on Emerging Nuclear Energy Systems (ICENES'96), **1**, Obninsk, Russia (1996).

15. A.V. Gulevich, A.P. Barzilov, O.F. Kukharchuk, et al., "Some Aspects of a Nuclear and Radiation Safety of a Coupled Pulse Reactor Systems," in Proc. of 2nd Int. Conf. on Advanced Reactor Safety (ARS'97), Orlando, USA (1997).

16. STIK Computer Code (the overview), Web Site of the Technical Physics Laboratory, http://www-tpl.ippe.obninsk.ru/english/activity/stik.html.

17. GRIF Computer Code (the overview), Web Site of the Technical Physics Laboratory, http://www-tpl.ippe.obninsk.ru/english/activity/grif.html.