XA04C1734

IGORR 6

Burnable absorber for the PIK reactor

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This research was supported by the State Scientific Center Program, Russian "Fundamental Nuclear Physics" Foundation, and "Unique Russian Installations" Program.

Abstract.

In the reactor PIK design a burnable absorber is not used and the cycle duration is limited by the rods weight. Designed cycle time is two weeks and seams to be not enough for the 100 MW power research reactor equipped by many neutron beams and experimental facilities. Relatively frequent reloading reduces the reactor time on full power and in this way increases the maintenance expenses. In the reactor core fuel elements well mastered by practice are used and its modification was not approved. We try to find the possibilities of installation in the core separate burnable elements to avoid poison of the fuel. It is possible to replace a part of the fuel elements by absorbers, since the fuel elements are relatively small (diameter 5.15mm, uranium 235 content 7.14g) and there are more then 3800 elements in the core. Nevertheless, replacing decreases the fuel burnup and its consumption.

In the PIK fuel assembles a little part of the volume is occupied by the dumb elements to create a complete package of the assembles shroud, that is necessary in the hydraulic reasons. In the presented report the assessment of such a replacement is done. As a burnable material Gadolinium was selected. The measurements for the beginning of cycle were performed on the critical facility PIK. The burning calculation was confirmed by measurements on the 18MW reactor WWR-M.

The results give the opportunity to twice the cycle duration. The proposed modification of the fuel assembles does not lead to alteration in the other reactor systems, but it touch the burned fuel reprocessing technology.

1. PIK reactor

The reactor is intended for basic research using neutron beams and irradiation facilities. The unperturbed thermal-neutron flux is as high as $1.3x10^{15}$ n/cm^{2}s in the reflector, and $4.5x10^{15}$ n/cm^{2}s in the central channel [1].
The reflector houses a cold-neutron source, an ultracold and cold neutron source, and a hot neutron source. Nine neutron guides branch off from the cold-neutron source and from the bottom of the channel immersed in heavy water and are led out into the neutron-guide hall. The reactor thermal power is 100 MW.
The core, 50 l in volume, is cooled by light water under pressure of 5 MPa. At the core center there is a light-water neutron trap with an irradiation channel, where the maximum thermal-neutron flux is reached. The core is surrounded by a 1-m thick heavy-water reflector (Table 1).

Table 1

PIK reactor parameters

Power	100 MW
Maximum thermal-neutron flux in reflector	$1.3x10^{15}$ n/cm^{2}s
Thermal-neutron flux in central channel	$4.5x10^{15}$ n/cm^{2}s
Core diameter	39 cm
Core height	50 cm
Coolant	H_2O at 5 MPa
Reflector	D_2O
Uranium enrichment	90%

Reactor construction started in 1976. After the Chernobyl disaster, construction was terminated, the reactor design was considerable refined and eventually agreed upon in 1991 as meeting the new safety and ecology requirements. By the beginning of 1998, construction of a reinforced-concrete confinement was completed, and installation of technological equipment, attributed to "important for the safety" class was resumed.

Based on its broad experimental potential, the reactor was intended to serve as an All-Union center of neutron research. Presently it is the only stationary research reactor under construction in Russia.

2. Controls

The heaviest control elements represent two rings at the boundary between the core and the light-water trap at the core center. The other eight control elements (plates) are located in the heavy-water reflector. Each element is provided by a separate electromechanical drive. The controls located in heavy water suppress considerably the thermal-neutron flux and are used for automatic (emergency) shutdown and for reaching criticality and raising power. The rings are intended to compensate burnup and, at the same time, as fast automatic shutdown.

While the total weight of the control elements is quite large ($11\beta_{eff}$), reliable shutdown, automatic shutdown, and compensation of heating and poisoning take up $7\beta_{eff}$, leaving only $4\beta_{eff}$ for burnup, which provides two-weak long power operation between refueling. It is this cycle that was intended by the project, but a longer, 30-40 day cycle, would be of considerable advantage for users.

Besides, prolongation of the cycle would bring considerable economical gain. Each refueling at the end of a cycle takes up about five days, which is a substantial fraction of the total cycle. This results in an increase of neutron fluence cost or, in other words, of the cost of each hour of reactor power operation.

The reactor will operate, as a rule, in a partial refueling regime. When loaded only by fresh fuel assemblies, the total reactivity is $17\beta_{eff}$. This figure is estimated by measurements made on the critical facility "Physical Model of PIK Reactor" (PM PIK) [2] and coincides with a calculated one [3].

The excess reactivity of $6\beta_{eff}$ is quite enough to increase the cycle duration up to 30-40 day, depending on the loading of the construction materials in the core for irradiation.

Several methods of increasing the campaign time may be considered. The version with arranging additional mechanical control elements in the core is unacceptable both because of the inevitable reduction of neutron flux and because of the need of introducing changes into the reactor vessel and the whole control system project. The reactor vessel is ready and is prepared for installation.

There was a proposal to poison the primary-circuit water with boron [4]. While this version can provide the necessary cycle, it has a number of serious drawbacks. One would have to design a new system of boron concentration control in the large volume of water in the coolant circuit (about 100 m^3) and in the communicating systems (more then 300 m^3). Also one would have to design a separate system for cooling the neutron trap with unpoisoned water to avoid decrease of thermal neutron flux in it. The neutron-physical characteristics of the reactor in an emergency would degrade. This relates primarily to the unavoidable decrease of the negative temperature coefficient, because a decrease in water density entails also a decrease in boron concentration in the core. Additional danger of an increase in reactivity under emergency reactor cooldown in the case of a rupture in the primary circuit appears. Besides, one will have to change the water-solution regime in the coolant circuit.

3. Burnable absorber

Preference has been given to versions with a burnable absorber. It is preferable in maintenance and in creation. All the changes are confined to the core, no change neither the control system nor the design of the coolant circuit.

The main drawback is in the fact, that it does not permit to adjust the reactivity in the cycle duration, if need. One would have to demonstrate the reliability in the reactivity calculation for burnable absorber as for other processes in the cycle. In any case, the safety in reactivity curve as a function of burnup have to be demonstrated.

The first complement of the fuel elements is delivered already, but changes can be introduced into the subsequent complements. To reduce these changes to a minimum, the version of absorber introduction into the fuel elements was rejected. The fuel element is the most crucial and conservative reactor element. In the PIK reactor a well tested design of the fuel element is used [1]. Introducing changes in its design will inevitably involve the corresponding changes in the well-organized production and will require new testing of fuel elements by the full program ensuring their reliability. It was a reason why we choose only the constructional material of the core for poisoning.

The first attempt was made with a shroud material by replacing stainless steel with zirconium - gadolinium alloy. In the frame of the homogenous assessment 3% of gadolinium was enough and such alloy can be easily done. Nevertheless the research and development must be done to create the production and to proof that it abide by national standards for the core construction material.

The PIK reactor core consists of 18 fuel-element assemblies of two types, square and hexagonal (Fig. 1). To level off the coolant velocity over the cross section, the fuel assemblies contain displacers - dumb elements, that do not contain fuel. It is these dumb elements that can be replaced most easily by burnable-absorber bar (BAB). Obviously enough, substituting BAB for part of the fuel elements would be less economical.

The objective of this work was to study the possibility of prolongation of the reactor operation cycle by replacing displacers with BAB elements. In this variant it is possible to use the only materials that are licensed for the core. The position of the displacers are fixed and can not be adjusted for better efficient. The neutron-physics problem reduced to exploring the possibility of compensating $4\beta_{eff}$ in order to attain minimum a 30-day cycle, and to studying whether variations in reactivity in the course of BAB burnup could present any danger.

Only three elements are used conventionally as burnable absorbers: boron, cadmium, and gadolinium (Table 2). Boron does not burn up deep enough during the campaign, and this results in increased fuel consumption. The first homogenous assessment of the residual by method [6] give 65% for boron 10, 3% for cadmium and 1.5% for gadolinium for 30 day of reactor operation. We chose gadolinium because of its having a larger cross section than cadmium and because in BAB aluminum matrix the amount of the heavy material is four time less.

TABLE 2

Nuclide	Natural content, %	σ ,2200 m/s, barn	σ PIK spectrum, barn	σ WWR-M spectrum, barn
Bor-10	20	3837	1541	2177
Cadmium -113	12.22	20600	19063	22721
Gadolinium - 155	14.8	60900	10494	20071
Gadolinium - 157	15.65	254000	41725	78617
Uranium - 235	90, enriched	681	273	378

The use of gadolinium, which has a larger burnup cross section than uranium, requires a careful analysis of the variation of reactivity during the operational cycle. One has at the very least to have the possibility of compensating the excess reactivity at any instant in the cycle, even if one, the heaviest control element, fails. It would be preferable to retain the smooth decrease of reactivity with BAB in the core.

4. Experiments on the PM PIK critical facility and WWR-M reactor

The "Physical Model of PIK Reactor" critical facility reproduces the reactor design within the core and heavy-water reflector. The fuel element assemblies are identical with those in the reactor, but the fuel elements, rather than being fixed in an assembly, can be removed from it. In place of displacers, one manufactured rods with BAB of four types, which contained 0.2 to 1.4 g Gd each. The gadolinium content was chosen based on preliminary calculations [7] and PM PIK measurements with cadmium strips. The BAB element arrangement is seen in Fig. 2. The results of the measurements are presented in Fig. 3. The required $4\beta_{eff}$ compensation is seen to be reached already with a gadolinium content of 0.7 g/BAB.

The calculated curve displayed in Fig. 3 was derived from the variation of the multiplication coefficient in the infinite cylinder model. The cells were calculated using the WIMS-D4 code [8]. The BAB coordinates are given in accordance with the schematic in Fig. 4. Each BAB and fuel element was approximated by a cylinder of the same volume, with their actual shape being disregarded. Only two gadolinium isotopes, 155 and 157, which dominate the cross section, were considered. While the experimental and calculated values do not fit, the discrepancy is seen to be reasonable.

It is impossible to check the gadolinium burnup calculations on the critical facility. One cannot even test the effect of burnup on reactivity with fresh fuel, because burnup changes the gadolinium isotope ratio.

To verify the burnup calculations, we carried out irradiation of ampoules containing BAB in the core of the 18-MW WWR-M reactor [9]. The BAB elements used in the test were loaded with 0.7 and 1.4 g/BAB.

The arrangement of BAB elements inside the ampoule is shown schematically in Fig. 5. The aluminum displacer at the center serves the purpose of avoid additionally softening the neutron spectrum, which in the WWR-M is softer than that of the PIK reactor as it is. Because any variation in ampoule reactivity in a high-power reactor is masked by a number of strong effects, we chose the relative measurement approach. We compared the reactivities of burning up ampoules with a complete-burnup imitator and reference ampoules with the starting gadolinium charge of 0.7 and 1.4 g/BAB. The absolute values of the initial ampoule reactivity with a gadolinium charge of 0.7 and 1.4 g/BAB were, respectively, 0.84 and 1.0% $\Delta K/K$, which, on the whole, agrees with the calculation. These values remained constant for the references within ±10%, which characterizes primarily the variation of power distribution over the WWR-M reactor core.

The energies released in the surrounding fuel elements were taken as base data for the burnup calculation. These energies are calculated for each new reactor operation cycle by the two-dimensional method accepted in reactor routine operation [10]. The ampoules with BAB were considered as equivalent, completely immersed absorbing rods.

The relative reactivity measurements have an error not above 3%. The time of complete gadolinium burnup, i.e. the time at which the reactivity of a burned-up ampoule becomes equal to that of the complete burnup imitator, is determined with the same accuracy.

The results of testing of ampoules with gadolinium BAB elements are presented in Figs.6. We see that the main parameter, namely, energy production until complete burnup, coincides with the calculated value. As already mentioned, we accepted as indication of complete burnup the coincidence in reactivity, within measurement error, of the BAB burned-up ampoule with the complete-burnup imitator.

5. BAB burnup in the PIK reactor

We used in the calculations the method verified in experiments with ampoules on the WWR-M reactor.

The calculation scheme is presented in Fig. 4. Three characteristic groups of BAB elements are singled out. The first group of 36 BAB elements is located at the interface between the inner and outer fuel-assembly layers, close to the 3-mm thick water gap. The second 48-BAB group is placed at the minimum of energy release. The third group containing 60 BAB elements is fixed at the outer boundary of the core, in the high-energy release region. The burnup was calculated for each group separately, with the other two groups neglected. We calculated the dependence of K_∞ for an infinite cylinder on burnup.

The results of the calculations are plotted in Figs.7. Acceptable burnup is attained after 25 days of reactor operation. This relates to the complete core-refueling regime. The slowing down of the burnup of the core as a whole at the end of the cycle is due to nonuniform burnup in the BAB groups. Partial refueling regime will not present any difficulties, because the fuel assemblies removed are those that suffered the largest burnup.

The behavior of reactivity in the course of burnup is shown in Fig. 8 for a core loaded with fresh fuel and with 144 BAB elements containing 0.7 g Gd/BAB. We readily see that a 30-day long campaign has been achieved and, most essentially, there are no intervals with increasing reactivity. The reactor can be reliably shut down by the existing safety and control elements at any instant of time.

The reactor startup will be made with the first fuel load which does not contain BAB elements. Fuel assemblies with BAB will be loaded gradually. Such an arrangement will permit experimental verification of the safety of using BAB elements when going over to complete loading of burnable absorber into the core.

Acknowledgments

The authors are grateful to R. G. Pikulik, A. I. Alekhin, V. F. Samodurov, G. V. Paneva, and the WWR-M personnel for tests carried out on the operating reactor, and to the critical facility personnel, for assistance in measurements.

The authors thank A. N. Erykalov and Yu. V. Petrov for fruitful discussions.

The authors owe their gratitude to I. E. Isakas for the preliminary burnup calculations of BAB ampoules, which facilitated the choice of the calculations scheme.

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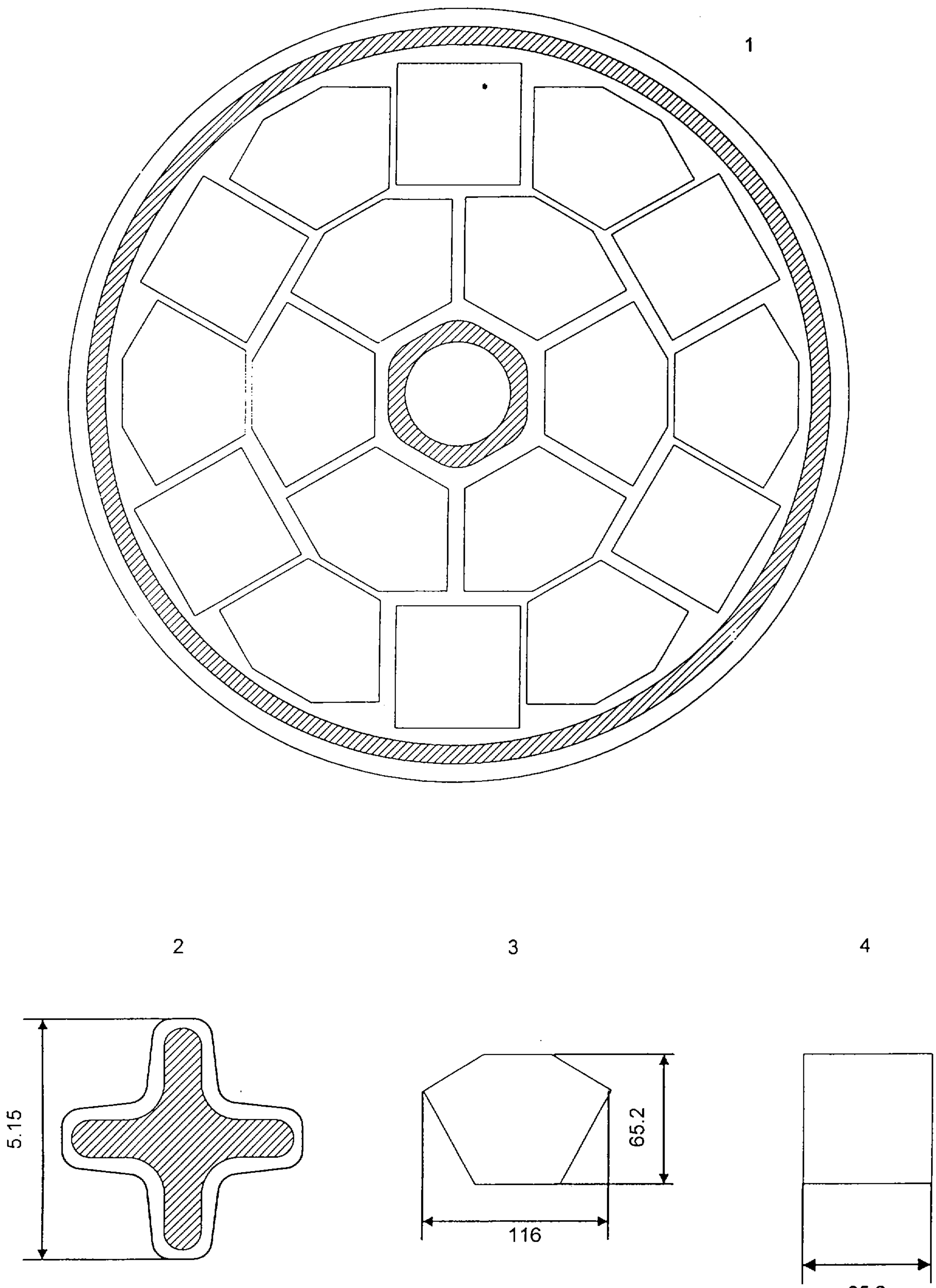


Fig.1. PIK reactor fuel element, fuel assemble and active core
1 - PIK reactor core
2 - Fuel element
3 - Hexagonal fuel assemble
4 - Square fuel assemble

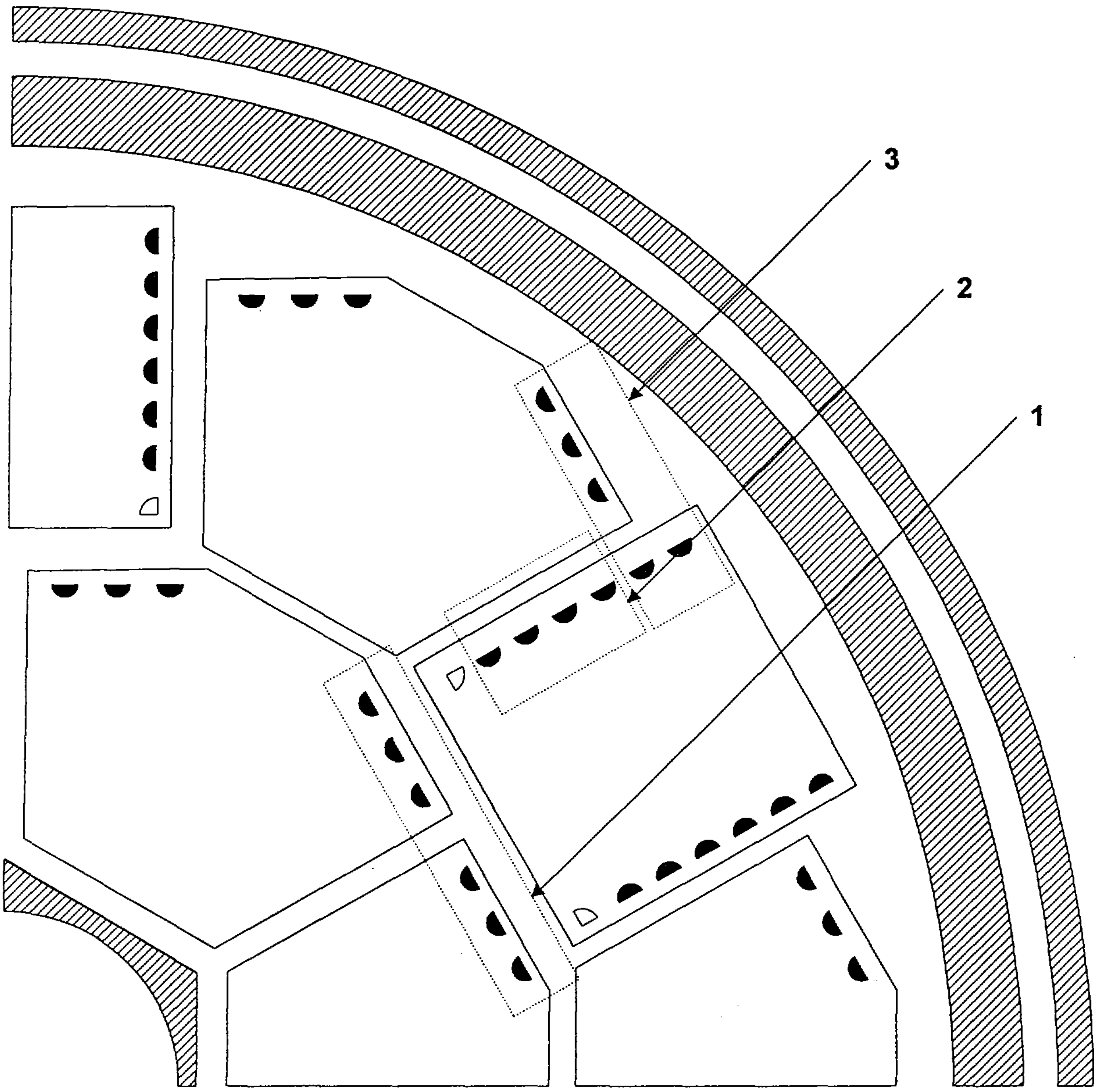


Fig.2. Burnable-absorber bar (BAB) arrangement
in the PIK reactor core
1 - The first group of 36 BAB
2 - The second group of 48 BAB
3 - The third group of 60 BAB

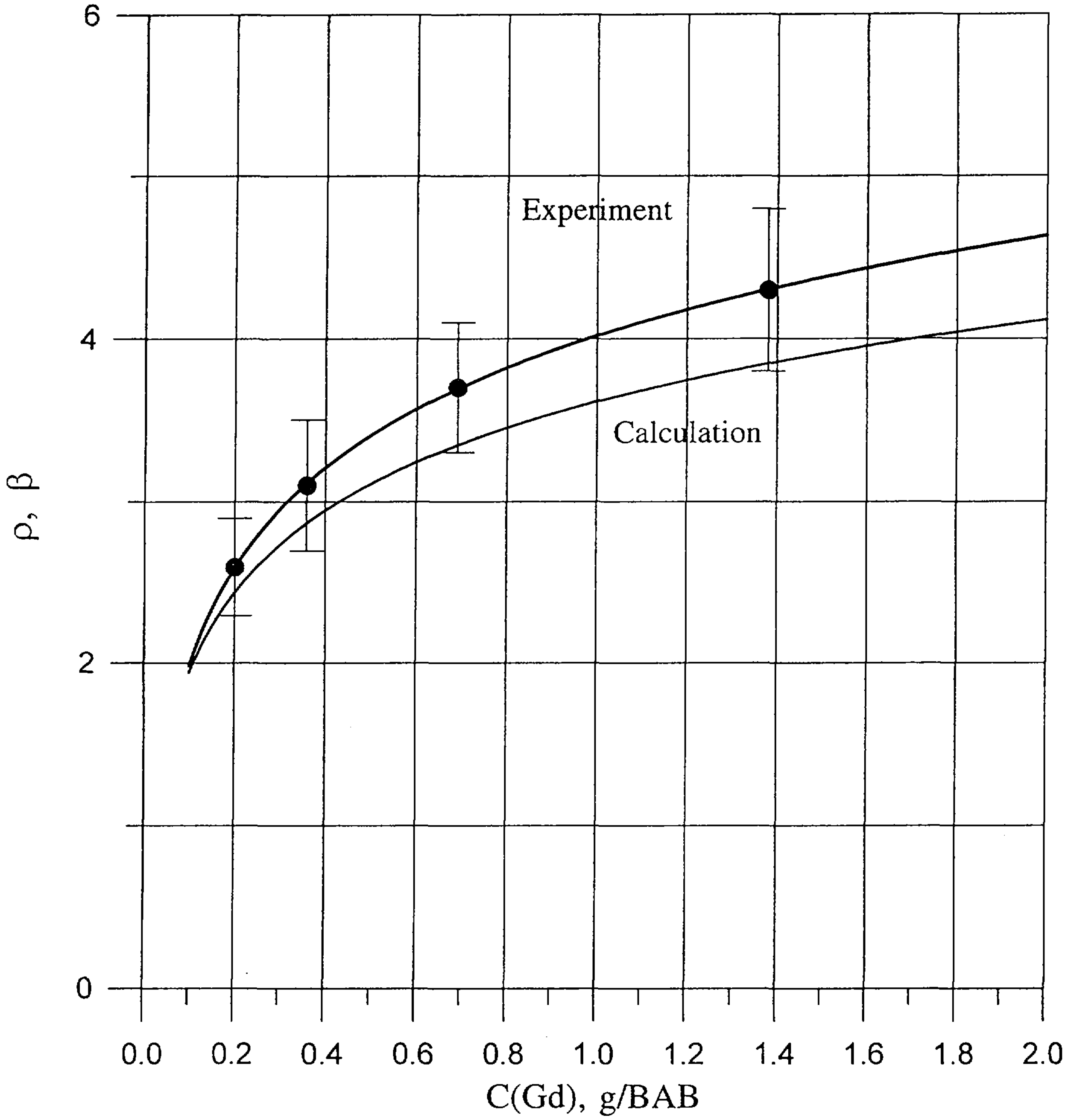


Fig.3. 144 BAB efficiency as function of gadolinium loading

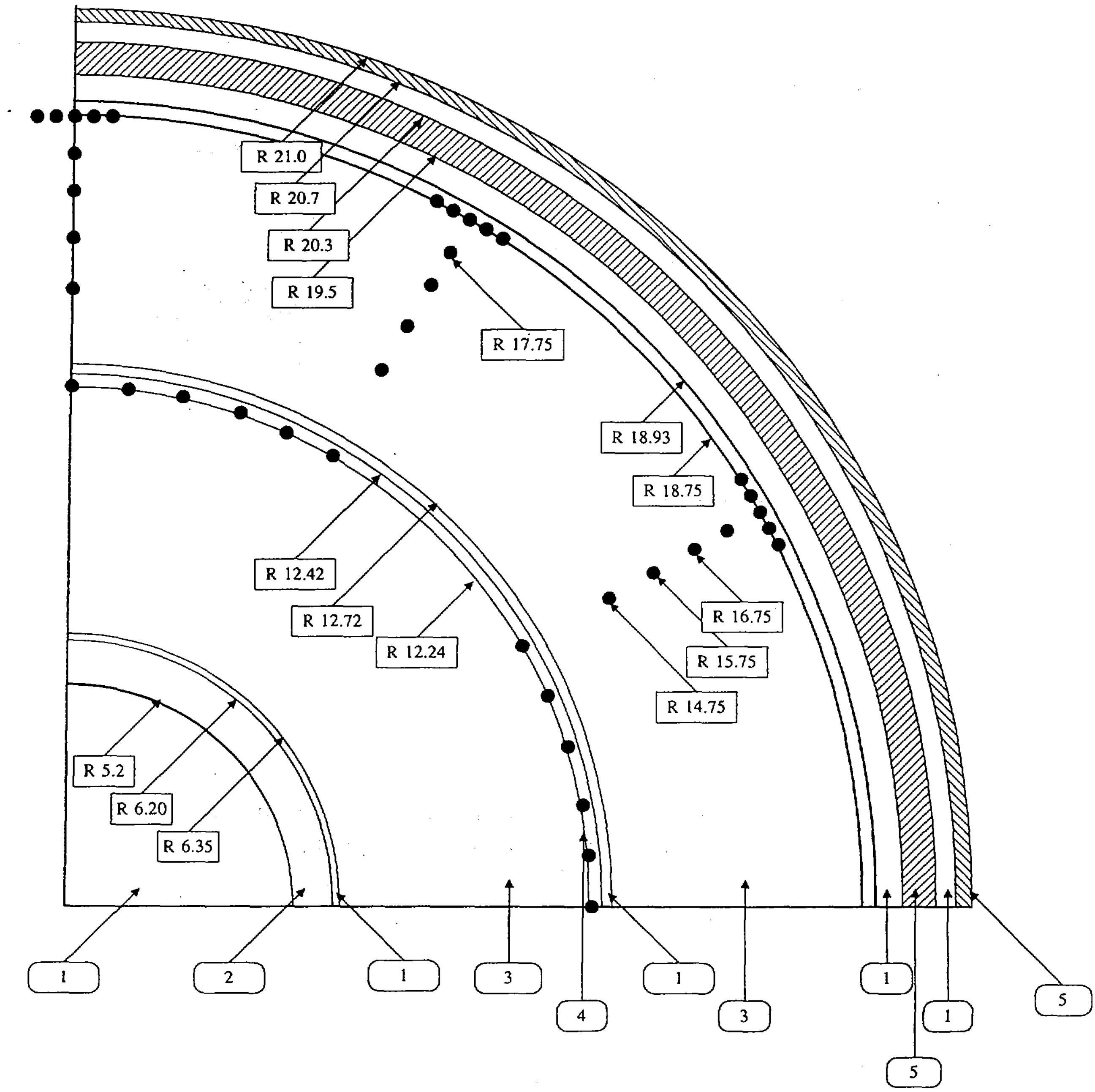
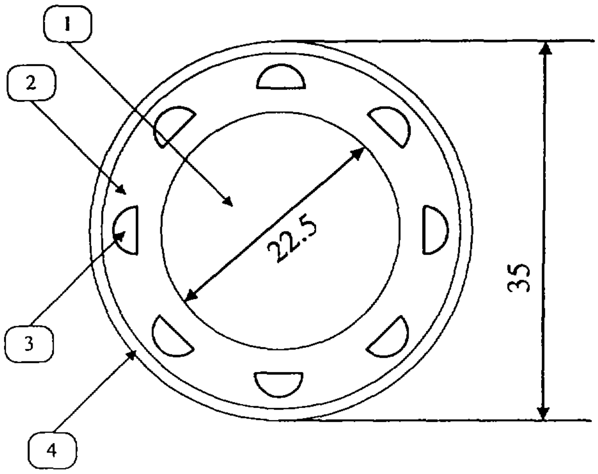


Fig.4. Burnable-absorber bar (BAB) coordinates
in the PIK reactor core calculation model.
1 - Water
2 - Zirconium
3 - Fuel
4 - BAB
5 - Stainless steel
R - radius in cm

Ampoule with BAB



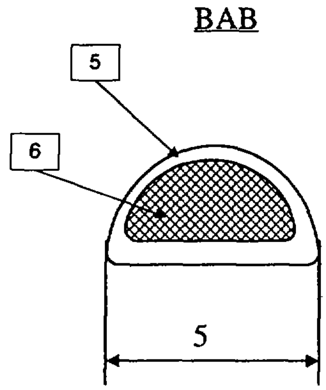


Fig.5. Burnable-absorber bar (BAB) arrangement in the WWR-M reactor ampoule.

1. Aluminium displacer
2. Water
3. BAB
4. Aluminium shroud
5. Zirconium
6. Zirconium and gadolinium oxides mixture

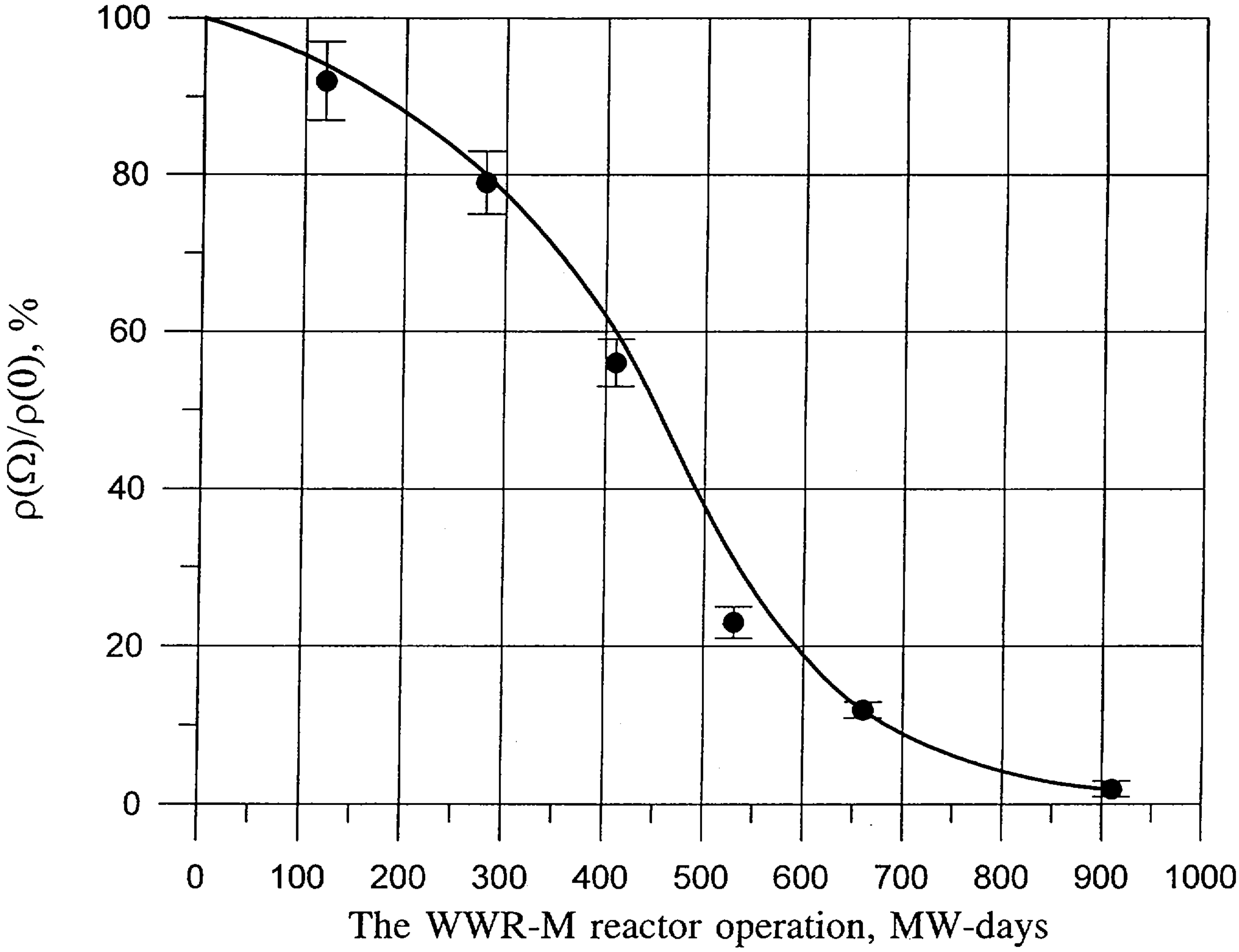


Fig.6. Ampoule relative reactivity in the course of burnup in the WWR-M reactor for gadolinium loading 1.4 g/BAB

● - experiment

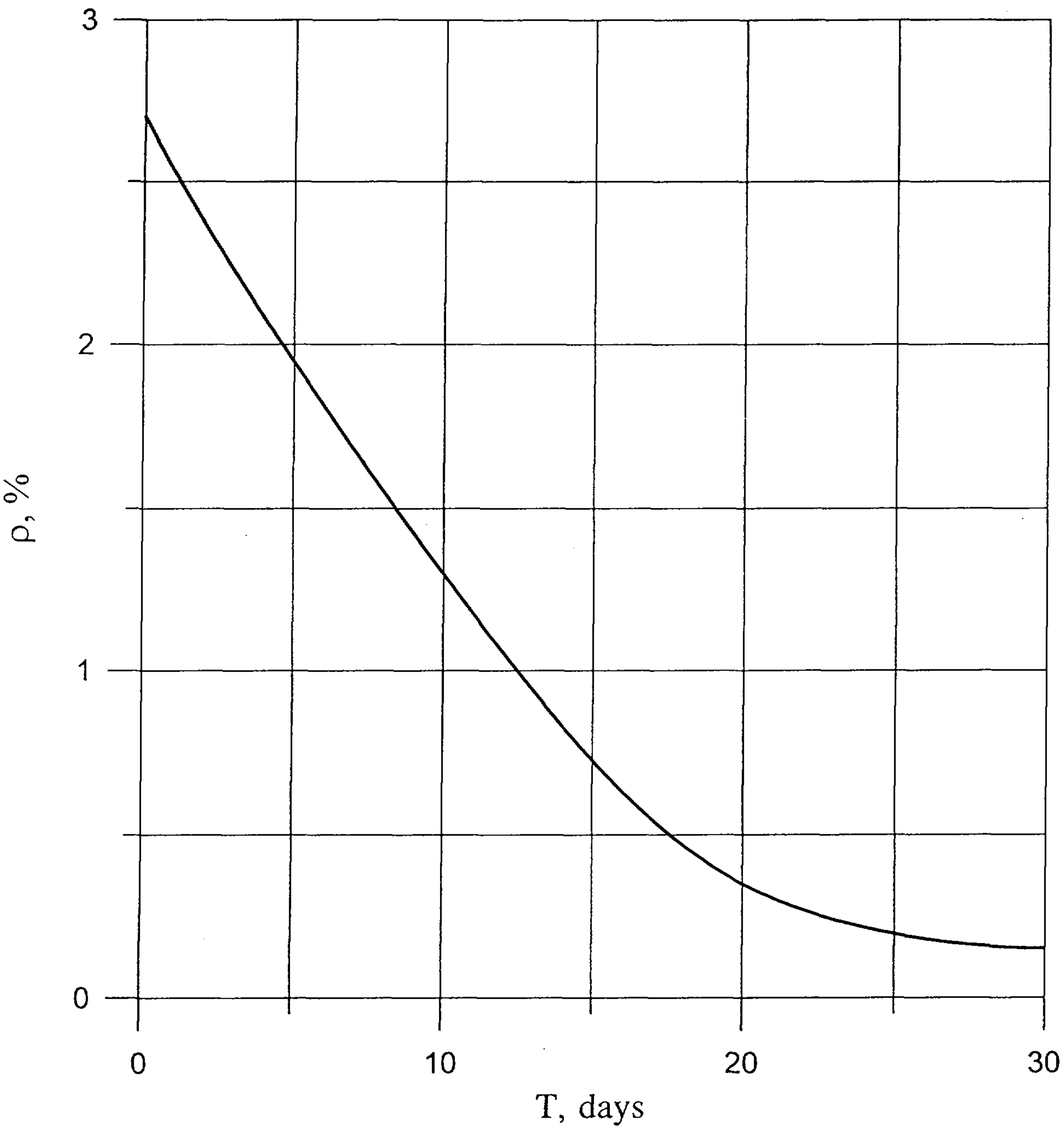


Fig.7. 144 burnable-absorber bar (BAB) reactivity in the PIK reactor calculated for an infinite cylinder

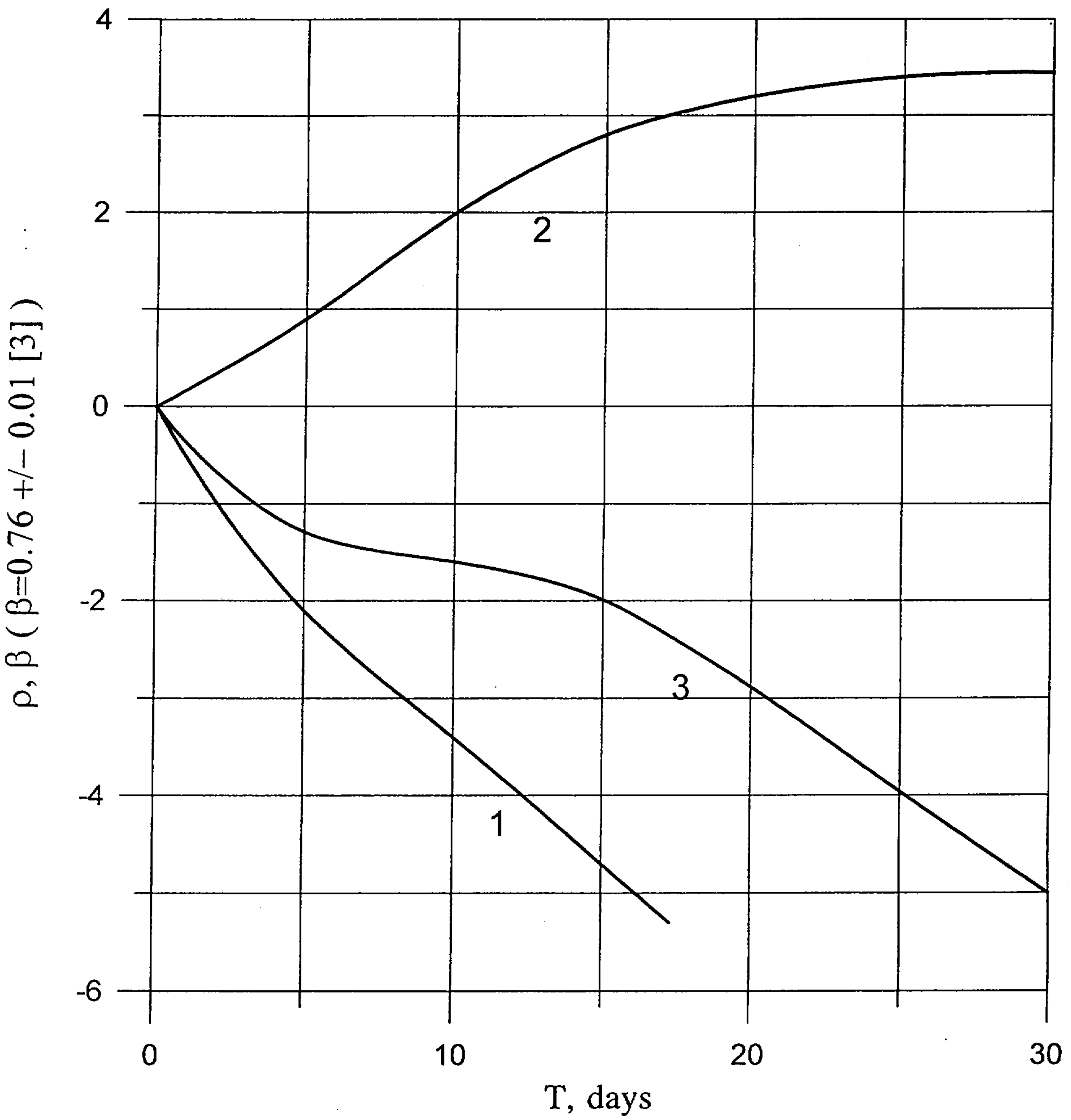


Fig.8. The PIK reactor reactivity in the course of burnup with loading 144 gadolinium burnable-absorber bar (BAB) containing 0.7 g/BAB calculated for an infinite cylinder.

1 - Fuel burnup

2 - Burnable absorber

3 - Resulting reactivity