IC/IR/98/1
INTERNAL REPORT
(Limited Distribution)

United Nations Educational Scientific and Cultural Organization
and
International Atomic Energy Agency
THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

CHOOSING THE OPTIMAL PARAMETERS OF SUBCRITICAL REACTORS DRIVEN BY ACCELERATORS

A.G. Khudaverdyan
Yerevan State University, 375049 Yerevan, Republic of Armenia

and

V.M. Zhamkochyan
Yerevan State University, 375049 Yerevan, Republic of Armenia
and
The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy.

Abstract

Physical aspects of a subcritical Nuclear Power Plants (NPP) driven by proton accelerators are considered. Estimated theoretical calculations are made for subcritical regimes of various types of reactors. It was shown that the creation of the quite effective explosion-safe NPP is real at an existing level of the accelerator technique by using available reactor units (including the serial ones).

MIRAMARE – TRIESTE
March 1998

Nowadays, in many countries with developed nuclear energetics, projects are elaborated where the problem of the explosion-safety of nuclear reactors should be solved. This problem is, at present, the most actual in the nuclear energetics development [1]. One of the perspective ways of solving this problem is investigations on subcritical reactors driven by accelerators [1-3].

As we showed earlier [4-7], the already achieved technology level permits to construct the explosion-safe NPP where the standard power water-moderated reactors of the VVER type are used in the subcritical regime in combination with the proton accelerator. The real possibility of the creation of the subcritical nuclear energetic plant for practical use is mentioned as well in the series of works by C.Rubbia et al., fulfilled by the experiment [8].

In this paper power reactors of various types, including the BN-600 fast breeder, are considered as the components of the system "proton accelerator-subcritical reactor". It was shown that the creation of quite effective and safe NPP is real at the existing level of the accelerator technique by using existing reactor units.

Let's consider a geometrically large reactor in which the neutron migration length M is much less than the size of active core. Since precision calculations of neutron fluxes were beyond the scope of this work, we restricted ourselves only to solving effective one-group diffusion equations. Such an approximation [9] was justified here because of the estimating character of all further conclusions. For the same reason the real reactors parameters in calculations were substituted by parameters of equivalent homogeneous systems [9] without taking into account the influence of neutron reflectors.

Thus, the stationary reactor equation has the form

$$\Delta\Phi + \frac{k_\infty - 1}{M^2}\Phi = 0, \quad (1)$$

where Φ is the scalar neutron flux and k_∞ is the multiplication factor for the given medium.

The target bombarded by the beam of accelerator protons was chosen as a cylinder made from an inactive substance with the radius r_0 and height H which is equal to the height of the reactor active core. As it is shown below, in the case of the reactors on thermal neutrons it is preferable to use the target surrounded by the fine cadmium shell. In this case all neutrons from the active core penetrating in the target region must be absorbed, and the neutron flux density in "out" direction, immediately on the external surface of the cadmium shell, should be conditioned only by fast neutrons knocking out by accelerator protons.

Hence, in the approximation of the Fick's law the source condition in this case may be written in the form

$$j = \left[\Phi/4 - D/2 \, \frac{\partial \Phi}{\partial r} \right]_{r=r_0}, \tag{2}$$

where j is the flux density of neutrons irradiated by the target surface, D is the one-group diffusion factor for the given medium.

In the absence of the absorbing shell and in neglecting the neutrons leakage from the "top" and "bottom" of the target, the condition (2) should be replaced by the following one:

$$j = - \left[D \frac{\partial \Phi}{\partial r} \right]_{r=r_0}. \tag{3}$$

Both conditions (2) and (3) correspond to the most optimal [10] - central disposition of the target-neutron source.

It should be noted that in our case the mean energy of external neutrons (at optimal energy of accelerated protons) is close to the mean energy of fission neutrons [11,12]. Thus, if we use the one-group approximation for fission neutrons, with the same precision we may use this approximation for external neutrons as well.

If geometrical sizes and migration area M^2 of the reactor are known, the value $k_\infty^{(0)}$ corresponding to the critical state in the rated working regime (without the target) can be determined. Particularly, for cylindrical reactors (which is the species we will consider below),

$$k_\infty^{(0)} = 1 + M^2 \left[(\xi/R)^2 + (\pi/H)^2 \right] \tag{4}$$

(see, for example, Ref.[13]), where $\xi \simeq 2,4048$ is the first root of the Bessel function $J_0(z)$; R is the extrapolated reactor radius. (For considered physically large reactors one may assume with sufficient precision that the active core extrapolated boundaries coincide with its geometrical ones.)

Radially-symmetrical solutions of Eq.(1) which satisfy the boundary conditions

$$\Phi(r,z)|_{z=\pm H/2} = 0, \qquad \Phi(r,z)|_{r=R} = 0 \tag{5}$$

may be written in the form [9]:

$$\Phi(r,z) = C \cos\left(\frac{\pi z}{H}\right) \left[J_0(\alpha r) - \frac{J_0(\alpha R)}{N_0(\alpha R)} N_0(\alpha r) \right], \tag{6}$$

where $J_0(x)$ and $N_0(x)$ are zero-order Bessel functions,

$$\alpha^2 = \frac{k_\infty - 1}{M^2} - \left(\frac{\pi}{H}\right)^2. \tag{7}$$

The expression (6) corresponds to positive values of α^2. If $\alpha^2 < 0$ one should replace functions $J_0(\alpha r)$ and $N_0(\alpha r)$ by modified Bessel functions $I_0(r\sqrt{-\alpha^2})$ and $K_0(r\sqrt{-\alpha^2})$.

We assume further that the distribution on the vertical coordinate for the flux density j of neutrons emitted by the target has the form close to $j = j_0 \cos\left(\frac{\pi z}{H}\right)$. (Giving up such an assumption should lead only to the excessive complication of expressions which hardly may be valid in the one-group approach.) In this case the source condition (2) leads to the following expression for the normalization factor C in Eq.(6):

$$C = j_0 \left\{ \frac{1}{4} \left[J_0(\alpha r_0) - \frac{J_0(\alpha R)}{N_0(\alpha R)} N_0(\alpha r_0) \right] + \frac{D}{2} \alpha \left[J_1(\alpha r_0) - \frac{J_0(\alpha R)}{N_0(\alpha R)} N_1(\alpha r_0) \right] \right\}^{-1}, \quad \alpha^2 > 0 \tag{8}$$

(with obvious changes for the case $\alpha^2 < 0$).

It is clear that the presence of the target in the active core at other fixed parameters of the system should lead to the appearance of the negative reactivity, and the value (4) for the multiplication factor here should not correspond to the reactor critical state. In the used approximation for such a critical state (at zero accelerator current) the boundary condition should be determined by going to zero of the left side of Eq.(2). Obviously, the denominator of Eq.(8) represents the expression which is proportional to j_0. Hence, equating this expression to zero and solving the equation on α, one may find the value α_{cr} (and with the help of Eq.(7) k_∞^{cr} as well) corresponding to the critical state in the presence of the target.

Following further the standard scheme of designations [9], we define the effective multiplication factor

$$k_{eff} = k_\infty / k_\infty^{cr}, \tag{9}$$

where k_∞^{cr} is the mentioned above value of k_∞ at which the reactor with the introduced passive target becomes critical.

If the real value of k_∞ remains the same ($k_\infty^{(0)}$) as in the rated critical regime (without the target), than when working with an accelerator we will have the subcritical regime with $k_{eff} = k_\infty^{(0)}/k_\infty^{cr} < 1$. (Values of k_{eff} for different reactors, obtained in such a way, correspond to the marks on the curves of Fig.3).

The problem of choosing the optimal value of the multiplication coefficients k_{eff} for the considered subcritical systems was discussed in a number of works [11,14-16]. We think the arguments of the authors of Refs.[15,16] are quite warranted and the condition $k_{eff} = 0.98$ is enough to provide the safety regime for reactors driven by accelerators. In any case, for systems containing the serial (but not specially constructed) reactor units, this condition could be considered as a reasonable compromise between the quest to make the system at most subcritical and real requirements for the neutron flux distribution in the active core.

In calculations for the parameters of different types of reactors, the data of Refs.[17-19] were used. As mentioned above, for each reactor the supposed target represented the cylinder of a non-active material with the height equal to that for the reactor active core. The target diameter was assumed to be 17 *cm*.

Note that the target sizes should, generally speaking, satisfy to the conditions of total absorption of accelerated protons, multiplication of the cascade-evaporative neutrons at their inelastic interactions with target nucleus and reflection of the neutrons flying backward and forward with respect to the proton beam [14]. The mentioned target diameter (17 *cm*) was defined by the beam profile (d=3 *cm*) and by deviation of protons due to their multiple scattering [20]. As to the target length, it should be, according to Refs.[11,21], no less than 61 *cm* if the natural uranium as a material is used. (This condition one may consider evidently fulfilled for any large reactor.)

In Fig.1 the calculated curves which determine the normalized distribution $\Phi(r,0)/\Phi_{max}$ of neutron fluxes in active cores of different reactors on thermal neutrons working in the subcritical regime ($k_{eff} = 0.98$) with the target of described type are presented; Φ_{max} is the maximum value of the neutron flux for the given reactor at fixed accelerator current. (Remember that presented curves correspond to the equivalent homogeneous reactors with all arising approximations.)

Apparently, from the viewpoint of the uniform power extraction throughout the active core, the best distribution corresponds to the Molten Salt Graphite Breeder MSBR-1000. We think the distribution for the VVER-type reactors may also be considered acceptable, especially if one takes into account necessary corrections for real reactors.

It should be noted that when using the targets without absorbing shells, the neutron flux distributions in the subcritical regimes for considered reactors become much more unfavorable with all resulting from here consequences.

When the power characteristics of subcritical systems were determined, the expression (6) for the flux was integrated for each reactor over the whole active core volume V (taking into account Eqs.(7)-(9)).

First of all it is of interest to find out the maximum feasible power of systems depending on the effective multiplication factor. The maximum permissible density of energy extraction for each reactor is determined by the maximum flux value $\Phi^{(0)}_{max}$ when working

in the rated critical regime, from where we have the necessary condition $\Phi(r,z) \leq \Phi^{(0)}_{max}$ for working in the subcritical regime (at invariable constructive characteristics of the active core facilities). Hence it follows that comparing integrals $\int_V \Phi^{(0)}(\vec{r})d\vec{r}$ (the rated critical regime) and $\int_V \Phi(\vec{r})d\vec{r}$ (the subcritical regime with an accelerator, $\Phi(\vec{r}) \leq \Phi^{(0)}_{max}$), one may find the ratio of the maximum permissible power $W_{max}(k_{eff})$ when working with an accelerator to the rated power of the reactor W_0.

In Fig.2 the ratios $W_{max}(k_{eff})/W_0$ are presented for a series of systems. At $k_{eff} = 0.98$ the values of W_{max}/W_0 for MSBR-1000, VVER-440 and VVER- 1000 are correspondingly 1.2, 0.57 and 0.46. The exceeding of W_{max}/W_0 over the unit for MSBR-1000 is immediately connected with the more optimal shape of the neutron flux distribution for this reactor working with an accelerator (see Fig.1.)

In the case of targets without absorbing shells the values of W_{max}/W_0 essentially decrease. In particular, for VVER-440 at $k_{eff} = 0.98$ the pointed value turn out to be only on the level $W_{max}/W_0 \simeq 0.35$.

Note that the optimal value of k_{eff} for each reactor was supposed to be established mainly by means of changing of the value of k_∞, at fixed active core main parameters.

The basic characteristic, determining the efficiency of an accelerator-reactor system, is the gaining coefficient G which is the ratio of the output electric power of the reactor W_{el} to the power consumed by the accelerator W_{ac} [8,11].

Let the working regime of the system be characterized by the mean neutron flux equal to $\overline{\Phi}$. Then, in the assumption of the uniform distribution of the active isotope mass M_u in the active core, the electric power of reactor will be

$$W_{el} = c_1 \, \kappa \, M_u \, \overline{\Phi} \, \sigma_f, \tag{10}$$

where c_1 is the factor depending on the active isotope mass number, κ is the efficiency in the transforming of heat into electricity for the given system and σ_f is the active isotope nuclear fission cross section at thermal energies.

According to Eqs.(6) and (7), the expression for the neutron flux in the given problem may be written in the form

$$\Phi(r,z) = j(z) \cdot \phi(r)$$

with the mean in the active core values

$$\overline{\left(\frac{\Phi(r,z)}{j(z)}\right)} = \overline{\phi(r)}; \quad \overline{\Phi} = \overline{j} \cdot \overline{\phi}. \tag{11}$$

(Remember that $j = j_0 \cos\left(\frac{\pi z}{H}\right)$ is the flux density of neutrons irradiated by the target.)

The total number of neutrons irradiated by the target in the time unit is $J = 2\pi r_0 H \overline{j}$, from where may be derived the expression for the proton accelerator current,

$$I_{ac} = \frac{e}{n} \cdot 2\pi r_0 H \bar{j},$$

and the expression for its consuming power,

$$W_{ac} = c_2 \cdot \frac{e}{n} \cdot 2\pi r_0 H \bar{j} \cdot T_p, \quad (12)$$

where c_2 is the factor accounting for unproductive power losses in the accelerator system, e is the proton charge and n is the neutron yield per one proton for the given target substance and at the given accelerated proton kinetic energy T_p.

Taking into account Eqs.(10)-(12), one may write the expression for the gaining coefficient G in the form

$$G = c \, \frac{\bar{\phi} \, \sigma_f \, M_u \, \kappa}{r_0 \, H}. \quad (13)$$

While estimating the value of G it is very important to choose the optimal accelerator proton energy. From the results obtained in Refs.[4,8,11] one may conclude that in the given problem the most optimal region for the proton beam energy is near $T_p = 500 \ MeV$.

In Fig.3 curves are given which describe the dependence of the value G on k_{eff} for different types of reactors at the accelerator proton energies 470 MeV. Here we used the results of Ref.[11], according to which, at the energy mentioned, the value of n for the neutron yield from the uranium target is 17.3 *neutron/proton*. It was also assumed that unproductive power losses in the accelerator system take away 2/3 of the consumed power.

The calculations for the CANDU heavy-water systems, in view of the lack of other data, were performed only for the CANDU-220 type reactor.

As follows from Figs.1 - 3, the subcritical system, based on the MSBR type reactor, has a considerable advantage over other systems with serial reactors practically in all indices. At the same time, it is necessary to mention the quite effective subcritical working regime of PWR and VVER type reactors. It follows also from Table 1 where values are presented for the maximum output electric power W_{max}, the accelerator current I_{max} and the gaining coefficient G for all considered systems at fixed $k_{eff} = 0.98$ and $T_p = 470 \ MeV$.

Table 1.

Reactor	MSBR-1000	PWR-1300	BWR-1270	HTGR-1160	CANDU-220	VVER-1000	VVER-440	AMB-II (200)	RBMK-1000
$W_{max}(MWt)$	1196*)	437	203	494	118	459	252	120	195
$I_{max}(mA)$	2.7	3.5	2.5	7.4	7.2	3.8	2.0	1.4	7.2
G	315	90	59	48	11	87	87	62	19

*) The power may be reduced to the nominal value (1000 MWt) by proportional reducing of the accelerator current.

Recalculation of results of Table 1 for other accelerator proton energies T_p may be performed using the data presented in Ref.[11].

The least adapted for the working in common with accelerators one should consider the serial heavy-water reactors, for example, of the Canadian CANDU type. Such a conclusion one could make beforehand. Indeed, working on the natural or even on waste uranium, at more sizable neutron fluxes, the heavy-water reactors at equal power should require more intensive neutron sources for the subcriticality compensation than other systems.

For the graphite and light-water reactors of the same-order power the important factor influencing on the working efficiency in subcritical regime is a surplus reactivity primarily provided in the unit. In this case, the most efficient prove to be systems having the minimal initial reserve of the reactivity. This, in particular, immediately follows from expression (13) where the value $\bar{\phi}$ at fixed k_{eff} is the rising function of $|\Delta\rho_M|$ - the module of negative reactivity introducing by the target-"trap" of thermal neutrons. As a consequence, the reactors with relatively small sizes (and, accordingly, with greater $|\Delta\rho_M|$) are found to be in a preferable position. As an example here the graphite breeder on the thorium cycle MSBR-1000 ($\Delta\rho_M \simeq -4 \cdot 10^{-2}$) may serve, the construction of which provides for the uninterrupted regulation of the fuel composition and, accordingly, the small reserve of reactivity on its combustion. An alternative example of graphite systems represents reactors of the RBMK type ($\Delta\rho_M \simeq -4 \cdot 10^{-3}$), the reequipment of which for working in the subcritical regime hardly may be considered expedient.

The highly important conclusion should be mentioned which follows from data of Table 1: the necessary proton accelerator currents for the reactors working in the subcritical regime ($k_{eff} = 0.98$) correspond to acting by now accelerators (see Refs.[14,22]).

According to the presented results, the serial light-water VVER and PWR type reactors occupy some intermediate position and, in principle, are quite acceptable at least in the initial stage of the introduction of subcritical systems. And what is more, at some reconstruction of systems based on these reactors, it is possible to improve essentially their output data when working with accelerators. The most simple variant of such reconstruction, according to Eq.(13), should include some decrease of the active core effective diameter retaining the former total mass of active isotope. So, for VVER-440 when the active core radius R decreases from 144 cm to 114 cm and the mean concentration of the active isotope ρ' increases from 2.4% to 3.8%, the gaining coefficient G at $k_{eff} = 0.98$ increases up to the value 152, and the maximal electric power W_{max} may be brought to the rated value 440 MWt. When diminishing R to 91 cm and increasing ρ' up to the level of 6 %, these values increase correspondingly up to $G \simeq 265$ and $W_{max} \simeq 520\ MWt$.

Let us now consider the results of analogous calculations for the reactor of BN-600 type on fast neutrons. Obviously, in this case in solving Eq.(1) it is necessary to use the source condition (3). This leads to the following expression for the factor C in Eq.(6):

$$C = \frac{j_0}{D\alpha}\left[J_1(\alpha r_0) - \frac{J_0(\alpha R)}{N_0(\alpha R)}N_1(\alpha r_0)\right]^{-1}, \quad \alpha^2 > 0. \qquad (14)$$

In the calculations we used the data on BN-600 and one-group parameters ($M^2 \simeq 300\ cm^2$, $D = 1.6\ cm$) for the BN-type reactors presented in Ref.[23].

Fig.4 presents curves which describe the neutron flux distribution $\Phi(r,0)/\Phi_{max}$ in the BN-600 active core at different values of k_{eff}. One should pay attention to relatively small distortions of the flux shape with the increasing of k_{eff} comparing with the analogous effect for reactors on thermal neutrons (see Fig.1). Hence, one may immediately make a conclusion about the efficiency of using BN-type reactors in the subcritical mode. The causes of such a behavior of curves are, on the whole, the relatively small active core dimensions and, correspondingly, essentially large values of k_∞ for each of the considered regimes. So, in the used approximation, the value of $k_\infty^{(0)}$ for the BN-600 reactor is equal to 1.69, while for example, for VVER-440, $k_\infty^{(0)} \simeq 1.03$.

In Fig.5 the curve is given which describes k_{eff}-dependence of the value W_{max}/W_0 for BN-600. Note that at $k_{eff} = 0.98$ we have for this reactor $W_{max}/W_0 \simeq 0.81$ while for the VVER-440 the analogous value proved to be only $W_{max}/W_0 \simeq 0.57$ (see Fig.2).

For the calculations of gaining coefficient G for BN-600, in view of the lack of necessary data, the Eq.(13) was unacceptable. In this case by means of Eqs.(6) and (14) one may obtain the value of the flux density amplitude $j_0 = j_0^{max}$ providing (at given k_{eff}) the maximum value of the flux (6), equal to the analogous value $\Phi_{max}^{(0)} = 10 \cdot 10^{15}\ neutron/cm^2 sec$ [23] in the rated critical mode. Integrating $j^{(max)} = j_0^{(max)}\cos(\pi z/H)$ over the lateral surface of the cylindrical target, we find the total number of neutrons irradiated by the

target per time unit in the maximal regime: $I_{max} = 4Hr_0 j_0^{(max)}$, whence it is easy to find corresponding values for the proton accelerator current and its consuming power. Using further obtained ratios $W_{max}(k_{eff})/W_0$, one may determine the values of G at different k_{eff}.

The values $G(k_{eff})$ and accelerator currents in the maximum regime $I_{max}(k_{eff})$ at the proton beam energy of 470 MeV, obtained by the described manner, are given in Fig.6.

According to the presented results, the tandem "BN-600 - proton accelerator" may become a quite acceptable power system and, as distinct from most of the system including serial reactors on thermal neutrons, even at values $k_{eff} \geq 0.95$. It follows both from sufficiently high gaining coefficients in the mentioned region of k_{eff} and from necessary currents of accelerated protons which correspond to already working accelerators [14,22].

At first sight, such a conclusion may seem paradoxical in view of the considerable neutron fluxes in BN-type reactors which are more than two orders of the magnitude greater than analogous values for the reactors on thermal neutrons. However, the source condition (3) connects the flux density j of external neutrons not with the flux Φ, but only with its gradient. Besides, as it was already mentioned, the shape of the distribution of Φ in subcritical modes turns out to be for BN-type reactors essentially more favorable than for large power reactors on thermal neutrons.

On the whole, similar results are valid for other present-day fast breeder reactors.

Acknowledgments

One of the authors (V.Zh.) would like to thank colleagues at the Abdus Salam International Centre for Theoretical Physics, Trieste, for useful discussions. He would also like to thank the Abdus Salam ICTP for hospitality.

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Figure captions

Fig. 1. The $\Phi(r,0)/\Phi_{max}$ ratios for different reactors depending on the relative radius r/R at $k_{eff} = 0.98$. 1 - MSBR-1000, 2 - VVER-440, 3 - VVER-1000, 4 - RBMK.

Fig. 2. Ratios of maximal feasible power W_{max} to the rated power W_0 depending on k_{eff} for different reactors. 1 - MSBR-1000, 2 - VVER-440, 3 - VVER-1000, 4 - RBMK.

Fig. 3. Gaining coefficients $G = W_{el}/W_{ac}$ depending on k_{eff} for different reactors. 1 - MSBR-1000, 2 - PWR-1300, 3 - BWR-1270, 4 - HTGR-1160, 5 - VVER-1000, 6 - AMB-II, 7 - RBMK-1000, 8 - CANDU. Marks on curves correspond to working regimes with rated values $k_\infty = k_\infty^{(0)}$ for the each reactor.

Fig. 4. Ratios $\Phi(r,0)/\Phi_{max}$ for the BN-600 reactor depending on the relative radius r/R at different values of k_{eff}. 2 - $k_{eff} = 0.98$, 3 - $k_{eff} = 0.96$, 4 - $k_{eff} = 0.94$. The curve 1 corresponds to the shape in the rated critical mode.

Fig. 5. The k_{eff}-dependence of the ratio W_{max}/W_0 for BN-600.

Fig. 6. The gaining coefficient G (a) and accelerated proton current in maximal mode I_{max} (b) depending on k_{eff} for the BN-600 reactor.

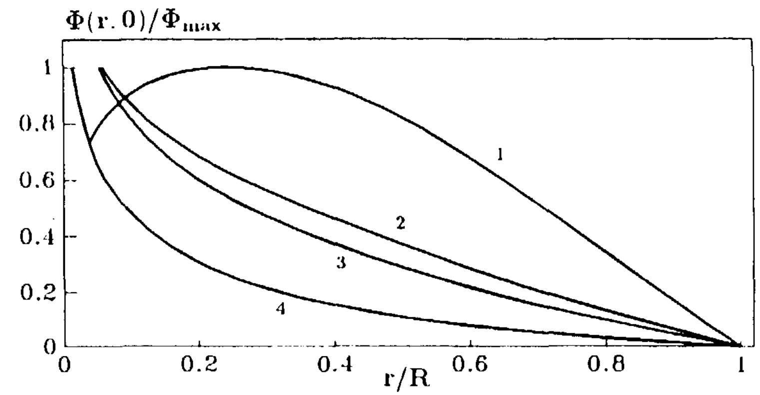

Fig.1

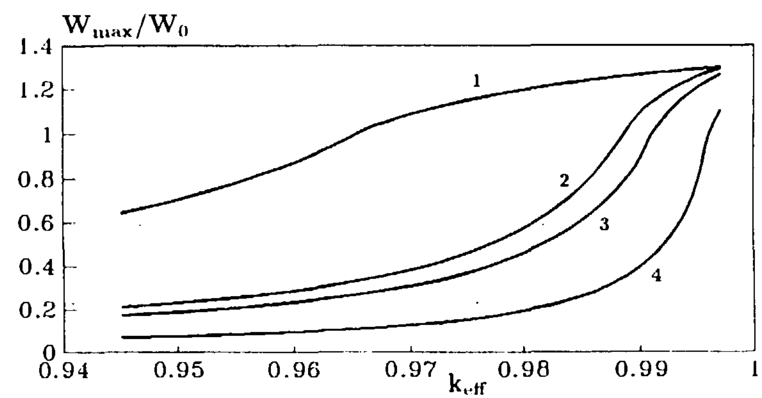

Fig.2

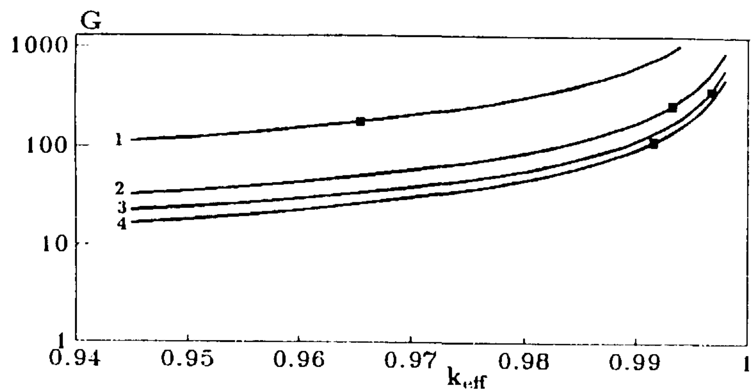

Fig.3a

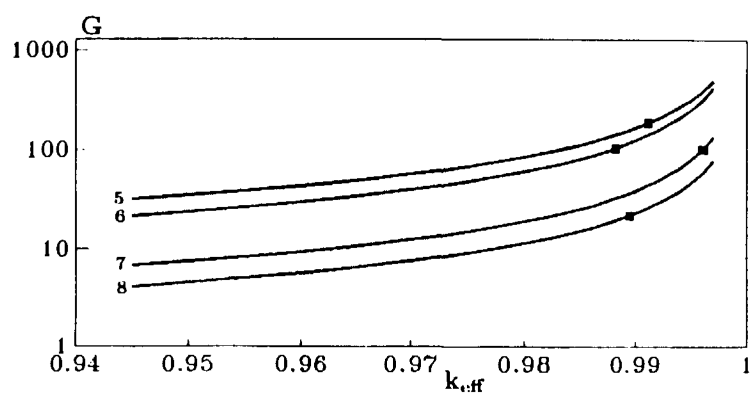

Fig.3b

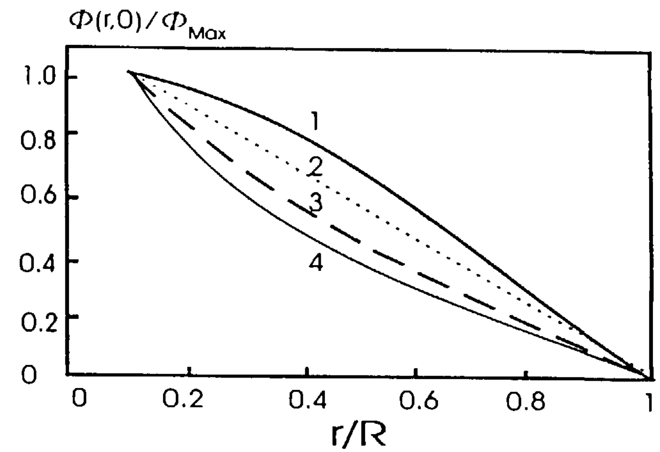

Fig.4

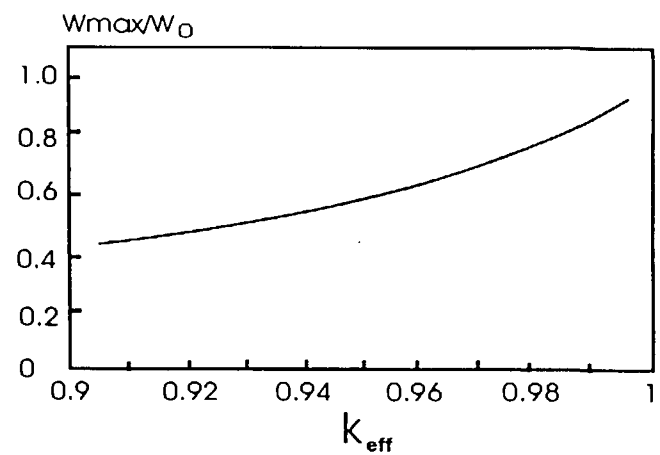

Fig.5

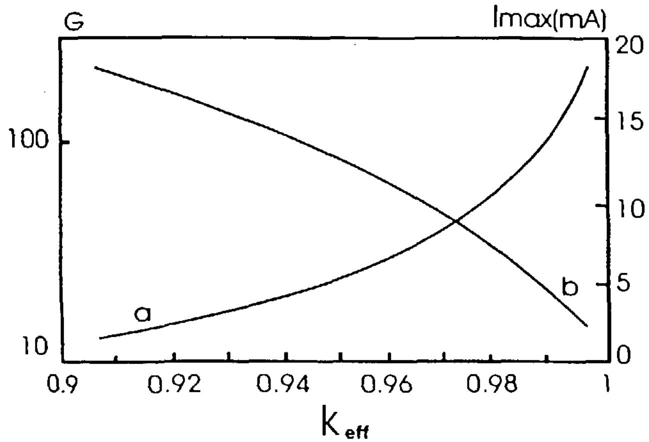

Fig.6