POWER RELEASE IN A SUBCRITICAL REACTOR

P.O. Demchenko, Ye.V. Gussev, L.I. Nikolaichuk

Institute of Plasma Electronics and New Methods of Acceleration NSC KIPT, Kharkov, Ukraine
e-mail: demchenko@kipt.kharkov.ua

Numerical simulation results of power release in a subcritical reactor in which the neutron field is generated under bombardment of an actinide target by a relativistic proton beam are given.

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1. INTRODUCTION

Now it is considered that the development of accelerator driven systems *(ADS)* will allow realizing a closed fuel cycle in nuclear power industry of the future. The *ADS* can be used for both the power producing and the transmutation of long-lived radioactive waste of the up-to-date industrial thermal reactors [1-3]. To obtain energy as a result of actinide fission by neutrons, it is supposed to use a subcritical reactor with the effective neutron multiplication factor of k_{eff}=0.96...0.98 [1,4]. The initial neutrons for such reactor driving are generated due to spallation reactions under bombardment of a heavy element target by relativistic protons.

In works fulfilled in *NSC KIPT*, the processes in a subcritical cylindrical reactor with the relativistic proton beam injection have been researched [5-8]. The fuel of this conceptual reactor was the homogeneous mixture of the depleted metal uranium and energetic plutonium. The isotope composition of utilized plutonium was identical to that contained in the spent fuel of a pressured water reactor of *WWER-1000* type with the degree of fuel burn-up about 40 MW·day/kg [5].

Including in the fuel cycle of depleted uranium with the ^{235}U isotope content not more than 0.2…0.3 %, which is a waste of nuclear fuel enrichment plants, as well as energetic plutonium, should help to solve two problems. Firstly, the utilization factor of natural uranium that now does not exceed of 0.6 % may be increased essentially. Secondly, the plutonium mass in the radioactive wastes, which are buried in geological depositories, may be also reduced considerably. Thus, it is possible to decrease considerably environment radiological effect of the up-to-date nuclear power, based on thermal reactors.

The specific of the considered conception of a subcritical reactor is the application of a spallation target from actinides for the initial neutron generation [5]. The neutron producing occurs when the relativistic protons are interacting directly with the nuclei of the uranium-plutonium blanket, but not with a separate target from stable heavy elements (tungsten, mercury, lead, bismuth). The accelerated proton beam is transported along the special ion guide and introduced in the blanket through a vacuum-tighten window as it was proposed for *Energy Amplifier* [4]. Thus, the target for producing of initial neutrons due to spallation cascades was the blanket region, which was filled with the stopping protons. The volume of the region was defined by transverse dimensions of injected beam and a proton stopping range. The stopping range l_b depends on a proton energy W and is determined by ionization and hadronic collisions in a substance of the blanket.

Such an actinide spallation target (a "*combined*" target) has some advantages in comparison to a target from stable heavy elements [1,4]. Firstly, at the chosen proton energy W the neutron yield per one proton is higher approximately in 1.5…2 times. As a result, the beam current I_b for producing of the needed strength of the initial neutron source may be reduced at the same times.

Fig. 1 shows taken from paper [10] experimental values of the neutron yield δ_{sp} for thick targets from the depleted uranium (0.2 % ^{235}U) and lead depending on the proton energy W. These values have been used in the present researches. The neutron yields δ_{sp} for uranium, given in other papers, almost 2 times exceed these for lead.

Secondly, the activation of stable element isotopes is eliminated (or reduced) due to application of a spallation target of actinides. Actinide nuclei in any case are used for the burning to produce the power.

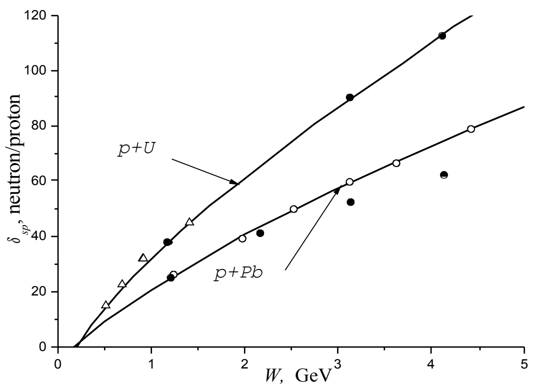

Fig. 1. *Dependences of the neutron yield in a thick target of lead and uranium* (0.2% ^{235}U) *on a proton energy* [10]

In the papers [5-8] the spatial performances of neutron fields, being formed in a subcritical reactor with the "combined" target, were studied in dependence on the effective neutron multiplication factor k_{eff}, radius R_0, length L_0 of a cylindrical blanket, a current I_b of a proton beam and its radius r_b. Calculations were made in the diffusion approximation. The space and temporal dynamics of nuclide composition in the subcritical uranium-plutonium blanket has been studied using calculated neutron flux $\Phi(r,z)$. It has been founded that densities some nuclides were functions only a proton beam fluence $F_b=I_b{\cdot}t$, while the densities of another isotopes were dependent on both the fluence and proton irradiation time t. The proton fluence values were defined at which some plutonium isotopes had reached equilibrium concentrations and the density of uranium nuclei decreased in two times (half burning of uranium) in the center of the blanket [5].

The aim of the present investigations was to study the spatial distribution of power density $p(r,z,t)$ released in the subcritical reactor blanket and power density time dynamics during irradiation by proton beam.

2. BASIC MECHANISMS OF POWER RELEASE

The considered cylindrical subcritical reactor is shown schematically in Fig. 2 [5]. The energetic plutonium concentration in a depleted uranium factor was varied from zero up to the value when the multiplication blanket was equal to k_{eff}=0.96. If the effective multiplication factor k_{eff} is chosen, then the plutonium concentration C_{Pu} in a blanket depends on reactor dimensions. For definiteness the most of simulations were performed for the reactor radius of R_0=40 cm and length of L_0=120 cm. The proton energy was assumed of W=1 GeV and a beam radius of r_b=5 cm. For the considered model of a conceptual reactor, the effect of a coolant and construction materials were not taken into account. So, it was supposed that all reactor volume was filled with a fuel.

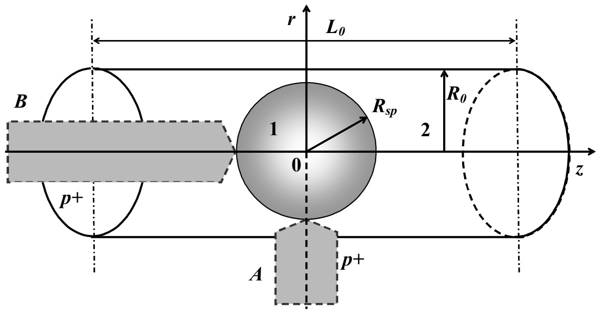

Fig. 2. *Geometry of a subcritical reactor: 1-spallation region, 2-external burning area (A, B are variants of radial and axial injections)*

The most data were obtained for two blanket compositions: the depleted uranium and uranium-plutonium mixture with k_{eff}=0.96. For chosen reactor dimensions and k_{eff}=0.96 the initial mass of uranium was of m_U=10.13 tons, and plutonium one of m_{Pu}=1.15 tons. Respectively, the plutonium concentration was of $C_{Pu}=m_{Pu}/(m_U+m_{Pu})\approx10.2$ %. Consequently, the initial mass of plutonium loaded in a subcritical blanket equals approximately to the annual plutonium yield being produced by 5 industrial pressurized water reactors of *WWER-1000* type (the basic thermal reactor in Ukraine). The source strength S of initial neutrons, generated by a proton beam, is $S=I_b{\cdot}\delta_{sp}/e$, and the source volume is defined with the region, occupied by a stopping beam $V_{sp}=\pi r_b^2{\cdot}l_b$ (where e is the proton charge) [5].

To simplify of the calculation the real blanket volume (expending cone) filled with a stopping beam was extrapolated with a sphere of equal volume V_{sp} localized in the blanket center (Fig. 2). Here, two possible directions of the beam injection are shown. The equivalent sphere radius is $R_{sp}=(3r_b^2l_b/4)^{1/3}$. As a result the blanket volume may be divided into 2 parts: spallation region $(r^2+z^2)^{1/2}\le R_{sp}$ (region 1, Fig. 2) and external region $(r^2+z^2)^{1/2}>R_{sp}$, where neutron diffusion and actinide fission by neutrons have place (region 2, Fig. 2).

The power density released in the spallation region is mainly defined with the next processes: the dissipation of beam power of $P_b=I_b{\cdot}W$, actinide fission (n,f) in the resulting neutron field [5], and actinide fission by high energy protons (p,f) [13].

The proton energy dissipation is caused both the interaction with electrons of blanket atoms (ionization losses) [11], and reactions of protons in collisions with blanket nuclei (nucleon-nuclear interactions) [12]. Fig. 3 shows the ionization proton range $l(W)$ in metal uranium and the linear stopping power dW/dx depending on proton energy W. The corresponding curves for $l(W)$ and dW/dx in uranium and plutonium almost coincide.

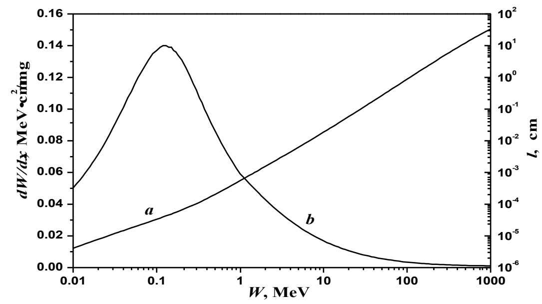

Fig. 3 *Dependences of* ***a*** *- proton stopping range l(W) and* ***b*** *- linear stopping power dW/dx in metal uranium on proton energy*

As it follows from Fig. 3, the linear stopping powers dW/dx in uranium and plutonium have maximum in the interval 100…150 keV, i.e. at the end of relativistic proton path, and decrease monotonously with the energy growth.

The proton stopping power resulting from nucleon-nuclear interactions (nucleus fragmentation and multiple particle production) increases with the growth of protons energy in a considered interval of proton energy $W\le$1…2 GeV [12].

In present work, the differential power losses of relativistic proton beam in the actinide blanket, caused by both the atom ionization, and the interactions with blanket nuclei, were not studied in detail. It was supposed that the beam power $P_b=I_b{\cdot}W$ dissipated approximately homogeneously in volume $V_{sp}=\pi r_b^2 \cdot l_b$, occupied by a beam, i.e. in the region of $(r^2+z^2)^{1/2} \le R_{sp}$.

Then the released power density $p(r,z,t)$ in the spallation region, can be presented as:

$$p(r,z,t) = I_b W / \pi r_b^2 l_b + \\ + \sum_i q_0 \bar{\sigma}^i_{nf} N_i(r,z,t) \Phi(r,z) \\ + \sum_i q_i \left\langle \sigma^i_{pf}(W) \right\rangle N_i(r,z,t) I_b / e\pi r_b^2 . \quad (1)$$

The first term of Eq. (1) is the power density p_b due to proton energy dissipation; the second term is the power density p_{nf}, which releases as a result of actinide fission by neutrons; the last term in the Eq. (1) is the power density p_{pf}, released under actinide fission by protons. Here $N_i(r,z,t)$ is the density of *i*-kind actinide nuclei in a blanket; $\bar{\sigma}^i_{nf}$ is the fission cross-section of *i*-kind actinide nuclei, averaged over a neutron spectrum in a blanket, and $\left\langle \sigma^i_{pf} \right\rangle$ equals to:

$$\left\langle \sigma^i_{pf}(W) \right\rangle = \frac{1}{l_b} \int_0^{l_b} \sigma^i_{pf}(x) dx = \\ = \frac{1}{l_b} \int_0^W \sigma^i_{pf}(W') \left(\frac{dW'}{dx} \right)^{-1} dW' \quad (2)$$

is the proton fission cross-section of *i*-kind actinide, averaged over proton stopping range l_b in a blanket substance; $q_0 \approx 213$ MeV is the energy per a fission of an actinide nucleus by fast neutrons [14]; $q_i \approx q_0$ is the average energy per a fission of an actinide nucleus by protons. Summing in Eq. 1 is taken over all actinides in a blanket. It is supposed that the fission energies by both the neutrons and protons for all actinides are approximately equal.

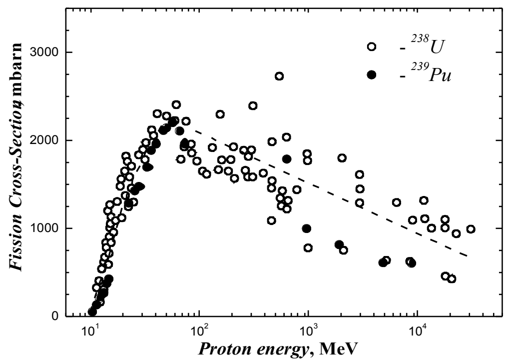

Fig. 4. *Fission cross-sections of ^{238}U and ^{239}Pu vs proton energy* [13]

To calculate $\left\langle \sigma^i_{pf} \right\rangle$ the experimental dependences of fission cross-sections uranium-238 and plutonium-239 on proton energy W were used, Fig. 4, [13], taking into account the proton linear stopping power dW/dx, Fig. 3. It was assumed that the proton fission cross-sections of all the plutonium isotopes as well as the americium isotopes are the same ones as given in Fig. 4 [13].

Outside of the spallation region $(r^2+z^2)^{1/2} > R_{sp}$, Fig. 2, the released power density is defined only with actinide fission by neutrons (photofission process was not taken into account):

$$p(r,z,t) = \sum_i q_0 \bar{\sigma}^i_{nf} N_i(r,z,t) \Phi(r,z) . \quad (3)$$

For simulation of the space distribution and time dynamics of power density according to Eqs. (1) and (3), neutron cross-sections from the database *ENDF/BVI.8* and the corresponding software were used [9]. The neutron field $\Phi(r,z)$ during the burning, which was stimulated with a proton beam, was supposed to be stationary. The nuclide densities of $N_i(r,z,t)$ were taken from solutions of the system of composition kinetics equations, which described the nuclear transformations in a blanket [5,6].

3. RESULTS OF POWER DENSITY SIMULATION

Fig. 5 shows the dependences of power density p on a proton beam fluence $F_b=I_b \cdot t$. The power densities p are normalized to a proton beam current I_b. Curves 1*a*, 2*a* illustrate the behavior of p/I_b in the center of spallation-region (r=0, z=0), and the dependences 1*b*, 2*b* at the point (r=0, z=10 cm), i.e. out of the spallation region. Curves 1(*a*, *b*) are given for the initial blanket composition from the depleted uranium, and curves 2(*a*, *b*) are given correspondently for a uranium-plutonium blanket with the effective multiplication factor of k_{eff}= 0.96. The dotted line 3 in Fig. 5 shows the averaged over the spallation region power density due to beam power dissipation of p_b/I_b=0.37 kW/cm³·mA.

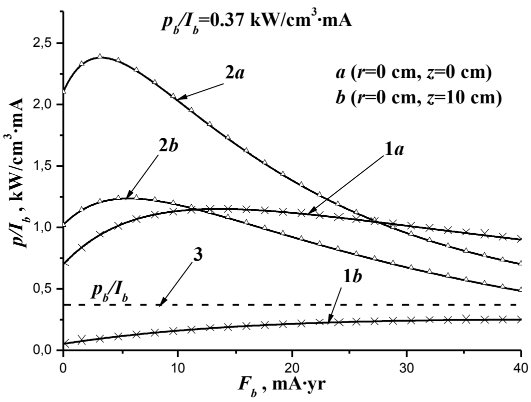

Fig. 5*. Dependences on the proton beam fluence of local power densities for depleted uranium 1(a,b) and uranium-plutonium (k_{eff}=0.96) 2(a,b) blankets*

Solid lines 1(*a*, *b*) and 2(*a*, *b*) in Fig. 5 correspond to the blanket irradiation by the beam current of I_b=1 mA, and markers by the beam current of I_b=10 mA. Thus, if a beam radius r_b and proton energy W are chosen then the power density, normalized to a beam current p/I_b, does not depend directly on a beam current I_b and on irradiation time t, but is only a function of the total proton fluence $F_b=I_b \cdot t$ and blanket parameters [5].

When the subcritical reactor starts (F_b=0 mA·year) with the initial blanket composition of depleted uranium (k_{eff}<<1) then the power density in the reactor center, caused by neutron and proton fission of actinides, is $p_f(0,0,0)/I_b$=0.33 kW/cm^3·mA, curve 1*a*, Fig. 5. At first the power density increases with proton fluence growth and reaches the maximum of $p(0,0,F_m)/I_b$= 1.15 kW/cm^3·mA at the fluence of $(F_b)_m$≈13.6 mA·year. The power density growth is caused with the conversion of uranium-238 in plutonium-239 (breeding), and contribution of plutonium fission in the total power release. When the proton fluence is equal to $F_b=(F_b)_{\rm m}$ the equilibrium plutonium concentration in the blanket center is reached and the power density growth is stopped. The subsequent proton irradiation $F_b>(F_b)_{\rm m}$ gives the monotonous decreasing of power density in the blanket center as the densities of uranium and plutonium nuclei are dropping due to actinides burn-up (curve 1*a*, Fig. 5) [5].

Out of the spallation region $(r^2+z^2)^{1/2}>R_{sp}$, if k_{eff}<<1, the neutron flux is rapidly decreasing with the distance. The reason is the strong neutron absorption in diffusion medium [5]. As a result, the released power density is essentially lower. In particular, at the distance of z=10 cm from the blanket center, at a point (r=0, z=10 cm), the power density is varying monotonously from p/I_b=53 W/cm^3·mA at the start of the reactor up to p/I_b=250 W/cm^3·mA for F_b=40 мA·year, and does not reach the equilibrium value, curve 1*b*, Fig. 5.

The addition of 10.2 % energetic plutonium to depleted uranium blanket results in the growth of the neutron multiplication factor up to k_{eff}=0.96. Respectively, the neutron flux in the blanket increases and a volume of formed neutron field expands considerably [5]. As a result the released power density is growing essentially both in the blanket center (curve 2*a*, Fig. 5), and outside of the spallation region (curve 2*b*, Fig. 5).

Since for chosen blanket parameters (R_0, L_0, k_{eff}) the initial plutonium concentration is less than equilibrium one [5], that is why there is initial growth of power density versus the proton fluence 2(*a*, *b*). The neutron flux distribution in a subcritical reactor is not uniform [5]. Therefore, the power density maxima are reached in corresponding blanket points for different values of proton beam fluence or correspondingly irradiation time. For the blanket center (r=0, z=0) and the considered blanket point (r=0, z=10 cm) the fluence values $(F_b)_m$ are equal to 3.32 mA·year and 5.74 mA·year, respectively. Accordingly, the normalized power densities p/I_b are 2.38 kW/cm^3·mA and 1.24 kW/cm^3·mA.

The spatial distribution of released power density outside the spallation region depends essentially on performances of generated neutron field $\Phi(r,z)$. As it had been noted [5,8], in a case of the strong subcritical blanket (k_{eff}<0.5) the specific dimensions of "burning" zone out of spallation region are defined by neutron diffusion path length in a blanket substance. If k_{eff} approaches to unity ($k_{eff}\to1$), the burning zone expands rapidly due to additional neutron multiplication, and a reactor transits to the critical condition. In this case, the dimensions of burning zone are limited only with the blanket geometry.

Radial distributions of normalized power density p/I_b in the transverse cross-section of the blanket by a plane z=0 are shown on Fig. 6. The curves of sets 1 and 2 are presented for depleted uranium blanket and a homogeneous uranium-plutonium one with k_{eff}=0.96 respectively. The curves (*a*,*b*,*c*) for every set of the curves are given for different proton fluence values F_b. These burning stages correspond to: *a* – the start of *ADS*; *b* – the fluence value at which the maximal density plutonium-239 is reached in the blanket center; *c* – the fluence value at which the initial density of uranium-238 decreases in two times in the blanket center (a half uranium burning up) [5].

As one may see, Fig. 6, the growth of k_{eff} results in the strong increasing both the local power densities and the total power of *ADS*.

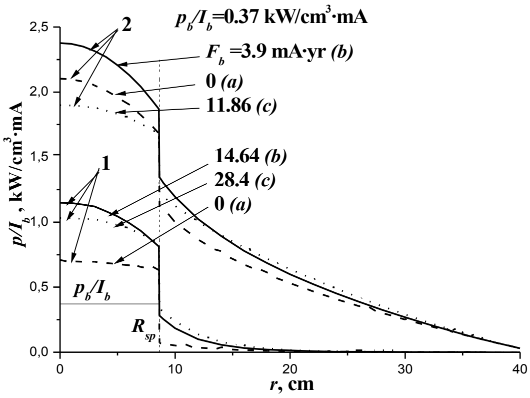

Fig. 6. *Radial distributions of power densities for depleted uranium 1 and uranium-plutonium (k_{eff}=0.96) 2 blankets*

The total power $P(t)$ or respectively $P(F_b)$ can be determined integrating the power density distribution $p(r,z,t)$ over a blanket volume of V (Eqs. (1) and (3)):

$$P(t) = \int_V p(r,z,t)dV = I_b W + P_{nf} + P_{pf} . \qquad (4)$$

It is known [1], the power P_{nf}, released in a subcritical reactor due to actinide fission by neutrons, is connected with the external neutron source strength of $S=I_b\delta_{sp}/e$ and the multiplication factor k_{eff} by the simple ratio:

$$\begin{aligned} P_{nf} &= q_0 S k_{eff} / < \nu > (1 - k_{eff}) = \\ &= q_0 I_b \delta_{sp} k_{eff} / e < \nu > (1 - k_{eff}), \end{aligned} \qquad (5)$$

where ν is the neutron yield per a fission.

The power, released due to the actinide fission by protons P_{pf} for chosen stopping beam model, is:

$$P_{pf} = q_0 \langle \sigma_{pf} \rangle N l_b I_b / e , \qquad (6)$$

where $<\sigma_{pf}>$ is the fission cross-section of uranium and plutonium isotopes by protons, averaged over a proton stopping range l_b; $N(r,z,t)=\sum N_i(r,z,t)$ is the total density of actinide isotopes nuclei in the blanket. Accordingly to Fig. 2, the uranium and plutonium cross-sections σ_{pf}

are approximately equal.

As it follows of (Eqs. (4) - (6)), the ratio P/I_b does not depend on a proton beam current I_b, and is defined by the blanket parameters, if beam radius r_b and proton energy are given.

A power amplification factor κ of *ADS* is a ratio of a power release P to a proton beam power:

$$\kappa = P/I_bW = \\ = 1 + q_0\delta_{sp}k_{eff}/\langle\nu\rangle(1-k_{eff})W + q_0\langle\sigma_{pf}\rangle Nl_b/W. \quad (7)$$

The ratio P_{pf}/I_b does not depend on k_{eff} and in accordance with (6) is determined only by the total density N of actinides and a proton energy W. For the chosen energy of W=1 GeV and the specific mass density of blanket ρ=18.7 g/cm^3, we have P_{pf}/I_b=0.51 MW/mA. Thus, the power, released due to actinide fission with protons, is approximately equal to 50% of beam power.

The main power generation in *ADS* is caused with the actinide fission by neutrons, i.e. the term P_{nf}, Eq.5. Even in the case of the depleted uranium blanket the value of P_{nf}/I_b is equal to 1.35 MW/mA. Thus, the fission power of uranium-238 nuclei by the fast produced neutrons exceeds the beam power of $P_b=I_b\cdot W$ in 1.55 times. As a result we have the power amplification factor κ=2.86 at the beginning of *ADS* operation for the blanket of the depleted uranium, i.e. the positive power yield. During the *ADS* operation, when the equilibrium plutonium concentration is reached (fluence of F_b=13.6 mA·year), κ is increasing up to κ=5 due to plutonium breading.

If the uranium-plutonium blanket with k_{eff}=0.96 was used we had $\kappa\approx$75.7 integrating the expression (4). But the estimation of magnitude κ using (5) and (6) gave a smaller value of κ=60. The discrepancy of the κ values is about 22 %. Such difference may be explained by the fact that the initial composition of the uranium-plutonium blanket for the chosen k_{eff}=0.96, had been calculated using a simple expression of $k_{eff}=k_\infty-L_D^2B_{10}^2$. This value was less than real one for the calculated blanket composition (k_∞ is the multiplication factor in an infinite medium, L_D is the neutron diffusion length; B_{10} is the buckling of a reactor [5,8]). The simplified estimation of k_{eff} did not take into account the *importance* of neutrons, i.e. the conjugated neutron flux [1,14]. The importance of neutrons determines the contribution to the multiplication factor of the neutrons with the different initial energies, and directions of movement, and points of generation. The calculations of the power amplification factor κ give the same values of κ=75.7 if instead of k_{eff}=0.96 one uses 0.968 taking in to consideration the importance of neutrons.

4. CONCLUSIONS

The present researches have shown that the specific of power density distribution in a blanket of *ADS*, namely the high power densities and the strong power density gradients, represents the complex problem for choice of construction materials and heat-hydraulics. The problem becomes essentially more complicated, if the *ADS* power must be compared to that of the up-to-date industrial thermal reactors of P~1…1.5 GW. In this case for the considered conception of *ADS* with an actinide target and k_{eff} = 0.98, one would have a beam current of I_b~9…14 mA for proton energy of W=1 GeV in accordance with Eq. (7).

As it follows from Fig. 6, the normalized power density in the center of *ADS* for k_{eff} = 0.96 reaches $p/I_b\cong$ 2.5 kW/cm^3·mA. Consequently, for a current of $I_b\geq$ 10 mA and a beam radius of r_b=5 cm, the released power density exceeds $p\geq$20 kW/cm^3, if a blanket consists of a metallic actinide mixture with the specific mass density of $\rho\approx$19 g/cm^3. Let us note for comparison, that the permissible power density in a fast reactor with a solid fuel and a liquid metallic coolant does not exceed 1 kW/cm^3 [14].

If a beam current I_b is given, the released power density in *ADS* can be reduced essentially increasing the volume, occupied with the external neutron source. That can be realized in several ways. Firstly, if instead of a metallic fuel it is used the oxides or nitrides of actinides with density of ρ=9…10 g/cm^3, which are applied as a fuel in fast reactors. As the actinide density drops more than 2 times accordingly the power density p also decreases. Application of UO_2 and PuO_2 mixture instead of metallic one increases simultaneously the fuel melting temperatures from T=1134ºC and 639.7ºC for uranium and plutonium to T=2840ºC and T=2390ºC for uranium and plutonium oxides, respectively [15]. Besides some volume of a blanket is partially filled with a coolant and construction materials in a real design of ADS. Simultaneously with the reducing of actinide density, the proton stopping range and respectively volume of spallation region are growing. Secondly, the transverse dimensions of an injected beam may be increased, in particular a beam radius r_b. However, the injection in *ADS* of wide-aperture beams represents a special problem. To increase a volume of a spallation region, the multi-beam injection of protons with the same total current may be considered. As a result, an extensive multi-connected region of stimulated burning may be formed with a lowered power density.

A variant of a high power *ADS*, so-called *Energy Amplifier*, was suggested in the work [4]. In this conception, a spallation target and a fissionable blanket are separated with a diffusion medium with low neutron absorption. The molten lead is used as a target and a diffusion medium. A flux of initial neutrons, which reaches a fissionable blanket, drops essentially due to expansion during the diffusion in lead. It results in decreasing of released power density in a blanket. The total lead mass is about 10000 tons.

The high power densities, generated in a subcritical reactor driven by a proton beam, may constrain us to refuse from a solid blanket of actinide oxides, nitrides or carbides and a liquid metallic coolant. In this case, the acceptable solution may be an *ADS* with a molten actinide salt blanket. A liquid salt conception of a subcritical reactor is now under study in some scientific centers.

As a conclusion, we note that the present study had been carried out to estimate the upper limit of parameters of a high power *ADS* with an actinide spallation target.

The important feature of *ADS* with uranium-plutonium fuel cycle and an actinide spallation target is the positive power balance even using the depleted uranium blanket. When this reactor starts, the power amplification factor is $\kappa \approx 3$ and increases during a proton beam injection until the plutonium concentration reaches the equilibrium.

Now it is evident that the development of a practical *ADS* design requires the tight cooperation of physicists, engineers, designers, economists and ecologists.

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ЭНЕРГОВЫДЕЛЕНИЕ В ПОДКРИТИЧЕСКОМ РЕАКТОРЕ

Е.В. Гусев, П.А. Демченко, Л.И. Николайчук

Приведены результаты численного моделирования энерговыделения в подкритическом реакторе, нейтронное поле в котором генерируется пучком релятивистских протонов при бомбардировке мишени из актинидов.

ЕНЕРГОВИДІЛЕННЯ В ПІДКРИТИЧНОМУ РЕАКТОРІ

Є.В. Гусєв, П.О. Демченко, Л.І. Ніколайчук

Представлено результати чисельного моделювання енерговиділення в підкритичному реакторі, нейтронне поле в якому генерується пучком релятивістських протонів при бомбардуванні мішені з актинідів.