CONCEPTION OF SECURE ATOMIC ENERGY PLANT WITH SUBCRITICAL REACTOR AND 100 MeV PROTON ACCELERATOR

A.N. Didenko, A.A. Glazkov, A.D. Koljaskin (MEPhI),
G.L. Horasanov (PhEI),
V.E.Kalantarov (ISDAP RAS)

1. INTRODUCTION

The possibility of Chernobyl-like accidents repetition and the danger of illegal weapon plutonium spread impel many laboratories to activate investigations on the problem of secure atom energy plants. The wide range of recent scientific publications [1-10] discusses really one conceptual version based on nuclear reactor and intensive neutron generator. Reactor is in subcritical state. The transition to working state is realized by extra neutrons produced by generator and injected into reactor active zone. The secure exploitation of energy system is defined by generator slow inertness allowing fast control of reactor total neutron flux. Moreover if needed it may be created neutron deficit more rapidly than by common ways which automatically stops reaction. The presence of a external neutron source assists to burn fuel completely and to increase the period of its loading. The problem of a weapon plutonium may be solved totally by means of reactor transfer to thorium cycle.

2. GENERAL RELATIONS

The main differences of various hybrid systems are connected with a diverse types of neutron generators. Here we don't discuss qualities of neutron sources based on electron accelerators or laser thermonuclear sources. We consider as the most perspective generators based on proton accelerator with the target placed in the nuclear reactor active zone or near it.

The purpose of the problem is to ensure the required extra neutrons flux which is defined by the relation:

$$N_g = \frac{P_r N(1-k)}{W_0 k_r}, \qquad (1)$$

where P_r is reactor electrical power, N - number of neutrons born in one fission event, W_0 - energy produced in one fission event, k_r - reactor thermal/electrical power transformation coefficient, k - reactor subcritical state level ("subcriticity"). If we suppose in (1) k_r = 0.3 and take k = 0.98 as a compromise between N_g-minimum and indefinite reaction cross-sections and nuclides concentration we get an estimation of the range $N_g = (0.5\div5.0)\times10^{18}$ n/s for reactors with electrical power $P_r = 0.1\div1.0$ GW. The creation of such neutron fluxes will take some energy, so in final as a security price will be some decrease of atomic plant power efficiency. That is why minimization of neutron generator power consumption becomes one of the principal problems.

The relation between accelerated particle beam current I and N_g value is defined by the formula (2) if we suppose that all target-born neutrons create extra neutron flux:

$$I = e\frac{N_g}{N_t}, \qquad (2)$$

where e is electron charge, Nt - neutron target yield depending on target material and on beam particle energy. For example Pb target and particle energy E = 0.1÷2.2 GeV N_t increases from 0.4 to 45 maximum. Targets made of Th, U and some isotopes have near values of N_t. The neutron target yield is the most important neutron generator parameter because it defines the accelerator current loading and approximately its energy consumption. Some investigators making their energy choice take E = 1 GeV [2-8] which corresponds to the maximum of curve $N_{norm}(E) = N_t(E)/E$ (see fig.1). In this case the relation $G_1 = P_r/P$ (P - beam power) reaches its maximum value.

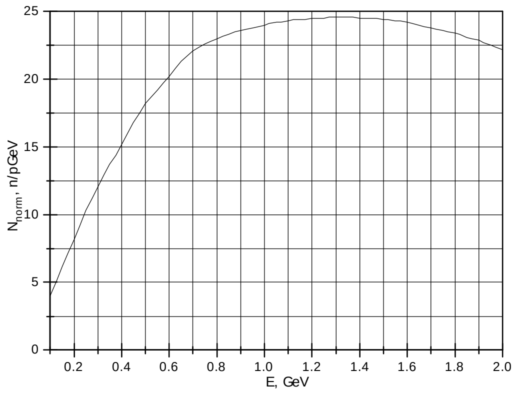

Figure 1. Yield of neutrons from Pb target.

3. COMPARISON OF TWO TYPE ACCELERATORS

Publications [2-6] present the neutron generator project with the parameters E = 1GeV, I = 10 mA for the reactor with the P_r = 0.675 GW. Protons are accelerated in the chain of isochronous cyclotrons. First two cyclotrons accelerate protons to 10 MeV, third and fourth cyclotrons accelerate them to 120 and 1000 MeV consequently. The calculations show that this system is well economical, but realization of it seems to be complicated because of the necessity to increase the beam current up to ten times to compare with the up-to-date cyclotrons.

It is interesting to compare the cyclic and linear accelerator advantages concerning this problem. It is natural to accelerate protons to high energies in a cyclic accelerators but in this problem their advantages are not so clear. Really neutrons flux is defined by the $I \cdot E \cdot N_{norm}(E)$ value. That is why neutron flux will be the same in the cases of linear (index l) and cyclic (index c) accelerator use if $I_l \cdot E_l \cdot N_{norm}(E_l) = I_c \cdot E_c \cdot N_{norm}(E_c)$. The most important characteristics defining the current limit is the current load which by the same current to the target in a cyclic accelerator will be n times higher than in a linear accelerator (n is number of orbits). It means that with the same current load in a linear accelerator it is possible to accelerate n times higher current if the accelerating frequencies f are equal or $n \cdot f_c/f_l$ times higher current if the frequencies are different.

The consequence of it says that to achieve the same number of neutrons in linear accelerator it is possible to use smaller energies since from $I_l \cdot E_l \cdot N_{norm}(E_l) = I_c \cdot E_c \cdot N_{norm}(E_c)$ we may see that I_l /Ic = $N_{norm}(E_c) \cdot E_c / N_{norm}(E_l) \cdot E_l \cong n \cdot f_l / f_c$. So it means that by the number of orbits in a cyclic accelerator n = 200 and by the $f_c = 0.1 f_l$ it is possible to decrease approximately 5 - 10 times the energy of ions accelerating in a linear accelerator to get the same neutron number. This is the main advantage of using linear accelerators to create subcritical reactors instead of cyclic accelerators.

4. INVESTIGATION RESULTS

As to linear accelerators, we may say that more detailed results may be reached after investigation of the dependence of power efficiency vs particle energy. Consider it in a more detailed way.

The authors of this paper have carried out the preliminary investigations on a parameters choice of neutron generator based on the proton linear RF accelerator. As the choice criterion is so-called energy gain G defined by the formula (3)

$$G = \frac{P_r}{P_{acc}}, \quad (3)$$

where $P_{acc} = P/k_{acc}$ is accelerator RF power; k_{acc} is accelerator power efficiency [10,11]. The formula for $(1/k_{acc})$ is:

$$(k_{acc})^{-1} = 1 + \frac{g}{2 I R_{sh} T^2 \cos^2(\varphi)}, \quad (4)$$

where T is a gap efficiency of accelerating structure, g = dE/dz is acceleration rate, R_{sh} is shunt impedance mean value along the accelerator, φ - synchronous phase. As a result we have established that with the fixed level of reactor subcriticity k each given P_r value has its corresponding $E = E_{opt}$ when G value reaches its maximum G_{opt}. Fig. 2 shows the curves G(Å) for reactors with various values of power Pr (curves 1-5) and $G_1(E)$ (curve 6) when target is made of Pb, values k = 0.98, R_{sh} = 80 MOhm/m, g = 2 MeV/m, T = 0.7, φ = - 45^0 they don't depend on energy E. G_1 function doesn't depend on P_r, its curve with some constant repeats $N_{norm}(E)$ curve normalized to proton energy. $G_1(E)$ curve maximum is reached when E = 1GeV, it is equal approximately to 30 if k=0.98. This extremal value may be considered as a G upper limit when there are no RF power losses in accelerator cavity walls. Taking into account RF losses and k_{acc} relation leads to some decrease of a real energy gain in the neutron generator-nuclear reactor system. The presence of 1-5 curves maximums may be explained by the competitive behavior of $N_t(E)$ and $k_{acc}(I)$ functions. In the low energy range the G decrease is connected with the neutron yield increase which is accompanied by the beam current decrease and as a consequence by the accelerator power feeding decrease. The G(E) decreasing part is tied with the prevalence of decreasing $k_{acc}(I)$ dependence. The use of cavities with lower efficiency leads to the displacement of maximums to low E range. If R_{sh} = 40 MOhm/m and reactors are of P_r = 100 MW then E_{opt} is approximately equal to 100 MeV.

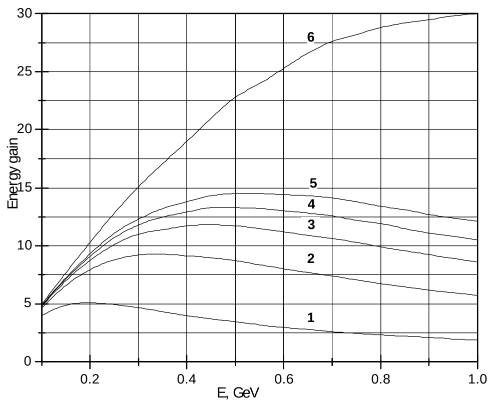

Figure 2. G for different P_r , GW: (1)-0.10;(2)-0.35;(3)-0.60;(4)-0.80;(5)-1.00;(6)-G_1.

Fig. 3,4 show the behavior of G_{opt} and E_{opt} curves as the functions of reactor power. In the range P_r = 0.1 - 1.0 GW G_{opt} and E_{opt} are increasing functions with the value ranges 4.9 - 14.5 and 0.18 - 0.5 GeV consequently. The average beam current is 50 - 90 mA, accelerator power efficiency is 55÷65 %.

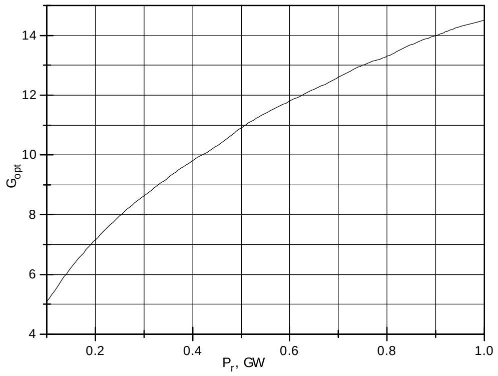

Figure 3. G_{opt} versus P_r.

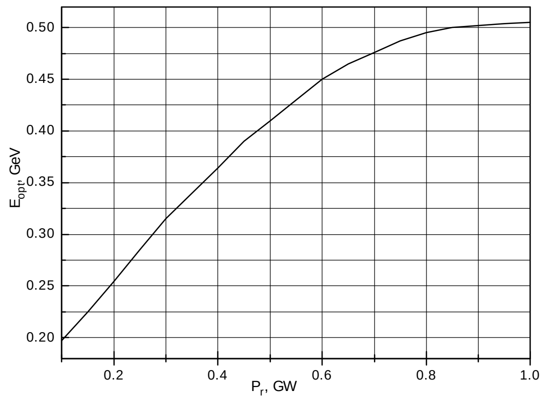

Figure 4. E_{opt} versus P_r .

5. CONCLUSION

The received results allow to make the next conclusions.

1. The energy gain is the higher when reactor power is the larger.

2. Even with P_r = 1 GW the required accelerated beam energy is 0.5 GeV which is two times less than usually considered value.

3. The parameters of neutron generator based on linear accelerator are really achievable because of the large experience stored during the research and developments of linear accelerators of this types.

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