

# POWER PLANT BASED ON SUBCRITICAL REACTOR AND PROTON LINAC\*

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## Abstract

Nuclear power plant based on accelerator driven subcritical reactor (ADSR) is considered. Such systems demonstrate higher safety because the fission proceeds in subcritical core and necessary neutron flux is reached with external neutrons generated in target of heavy nuclides. In order to efficiently use ADSR for energy production, it's needed the total power, generated in the reactor, to be greater than power inputs for charged particles acceleration. The plant driven by middle-energy accelerator, which is cheaper than high-energy accelerators, proposed for these purposes, is considered. So it's necessary to find other ways to amplify reactor power outputs. Thus, the technical solution to increase power gain of small-sized power plant with a linear proton accelerator (energy 300-400 MeV, average current 5 mA) is proposed. Thermal power up to 300 MW was reached.

## INTRODUCTION

Combination of high-power neutron sources with subcritical reactor systems, or so called hybrid systems or ADSR, are being researched in various countries. A proton accelerator combined with a target can possibly be considered as the required neutron source.

Nowadays projects of ADSR are being considered with proton and deuteron beams accelerated mostly up to 1 to 2 GeV. This tendency is explained by the fact that the nuclear waste transmutation is in the spotlight of the recent ADSR research program, although energy production is also considered. So it would be interesting to investigate the possibility to design a compact power plant with a thermal power output of 200...400 MW, which could be the basis of a safe nuclear power plant or a research complex for the transmutation of long-living radioactive isotopes. Such power plant doesn't require a large accelerator and huge investment and can be created,

for example, on the basis of middle-energy accelerator-driver which characteristics are presented in Table 1[1].

## NEUTRON GENERATION IN ADS TARGET

The ADS target should provide the maximum neutron yield under irradiation by the charged particles beam.

The spallation neutrons intensity is specified by the following expression:

$$S = \frac{I_p m_0}{e},$$

where  $I_p$  – the accelerator average current,  $m_0$  – neutron yield (the average number of neutrons generated in the target by one accelerated charged particle),  $e$  – the charge of an accelerated particle.

The neutron yield depends on the charged particles beam characteristics, target composition and sizes.

The neutron generating targets can conditionally be divided into two categories [2]: non-fissile (performed on the material which doesn't fission by neutrons) and fissile (performed on the fissile neutron generating materials).

In fissile targets the neutron yield is higher than in non-fissile, however the heat generation in them is significantly exceed one in non-fissile targets.

For non-fissile ADS targets could be used:

- high-melting targets of tungsten, tantalum, capable to carry high local energy releases;
- liquid metal (lead and lead-bismuth) targets, in which structural material changes under irradiation are absent.

The cylindrical targets optimal sizes irradiated by 300 MeV proton beam are presented in the Table 2. The neutron yield from these targets under the protons 200...400 MeV is presented in Fig. 1.

Table 2: Cylindrical targets optimal sizes. D (cm) – diameter, L (cm) – length, Z (cm) – deepening, N – relative neutron yield (neutron/ proton) in dependence of protons energy

Material	D <sub>opt</sub> , cm	L <sub>opt</sub> , cm	Z <sub>opt</sub> , cm	N, n/p
Pb	45.0	75.0	15.0	4.9
Bi	58.0	77.5	17.5	4.7
44.5%Pb- 55.5% Bi	50.0	75.0	15.0	4.7
W	7.0	14.5	1.5	3.6
Ta	7.0	14.3	1.3	3.4

Table 1: Proton linac main characteristics

Output energy	300 MeV
Average current	up to 5 mA
Duty factor	10%
Frequency range of RFQ and DTL	424 - 433 MHz
Beam power	1,5 MW

\*Work was partly supported by SPbSU, grant No. 9.38.673.2013

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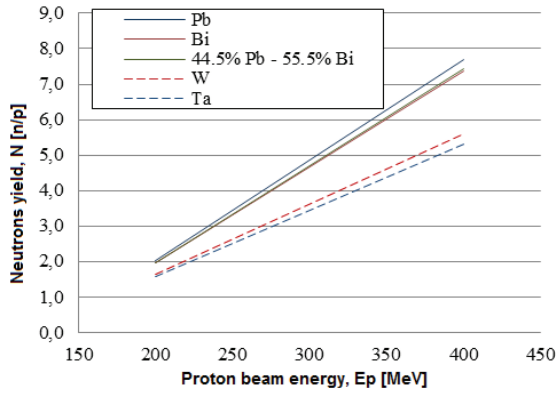


Figure 1: Neutron yield from the non-fissile cylindrical target surface with optimal sizes ( $E_p = 200 \dots 400$  MeV).

For fissile targets calculations all generated neutrons are divided into 2 categories: with energy over and lower 20 MeV. The multiplication of neutrons with energy  $< 20$  MeV is taken into account during the reactor core neutronics calculation, where standard neutron cross-section libraries (E-NDFL) are used. So for ADSR neutronics calculation we only take neutrons which overpass the 20 MeV level (spallation neutrons).

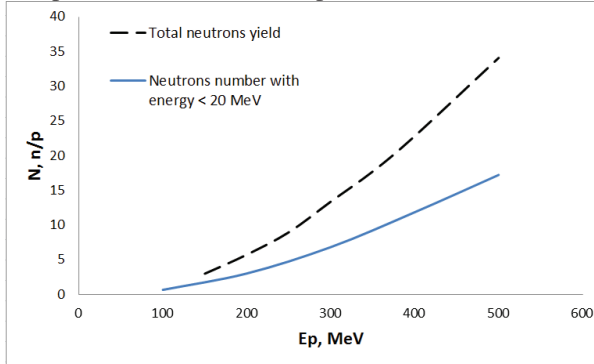


Figure 2: The dependence of spallation neutrons yield in  $U^{238}$  target on proton beam energy.

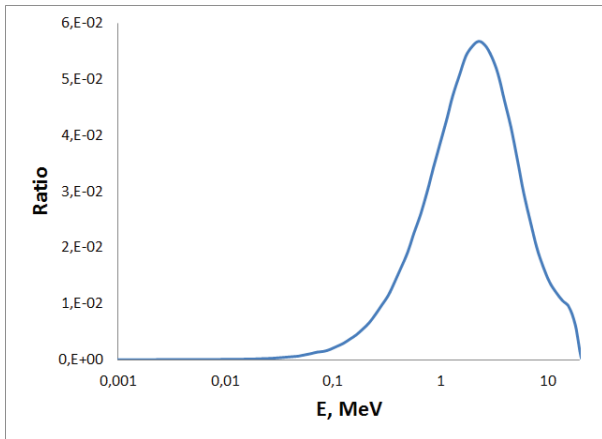


Figure 3: Energy spectrum of spallation neutrons in  $U^{238}$  target ( $E_p = 300$  MeV).

The yield of spallation neutrons for  $U^{238}$  and  $U^{235}$  is almost equal and is about 7 n/p. Thus for the considered accelerator (Table 1) the source intensity is about  $2.2 \cdot 10^{17}$  n/sec.

## POWER OF ADS SUBCRITICAL REACTOR SECTIONED CORE

The method aimed to ADS power amplification was proposed in several papers [3]. It is based on the reactor core sectioning. The sectioned reactor core consists of two sections: fissionable target and subcritical booster with broken coupling between booster and target. Then the fissionable target is the first neutron multiplying cascade, and the booster — the second multiplying cascade.

Multiplication factor of the sectioned reactor core:

$$k_{\text{eff}} = \frac{1}{2} \left( k_1 + k_2 + \sqrt{(k_1 - k_2)^2 + 4k_1k_2k_{12}k_{21}} \right),$$

where

$$k_i = k_{\infty i} P_{\text{fiai}},$$

$$k_{ij} = \frac{P_{\text{fijj}}}{P_{\text{fjaj}}},$$

sections  $i, j$ : 1 — fissionable target, 2 — booster,  $k_{\infty i}$  — infinite multiplication factor for  $i$ -th section composition,  $P_{\text{fijj}}$  — probability for neutron born in section  $i$  to be absorbed in section  $j$ .

Thermal power for the reactor core is defined by the formula

$$N_T = \frac{E_f Q_f}{\nu},$$

where  $E_f$  — energy released per a fuel nuclei fission.

For a sectioned reactor core  $Q_f = Q_{f1} + Q_{f2}$ , where

$$Q_{fi} = S_0 \frac{k_{0i} \left( \frac{1 - k_j}{k_j} \right) + k_{0j} k_{ji}}{\left( \frac{1 - k_j}{k_j} \right) \left( \frac{1 - k_i}{k_i} \right) - k_{ij} k_{ji}},$$

$k_{0i} = \frac{P_{S0ai}}{P_{\text{fiai}}}$ ,  $P_{S0ai}$  — probability for source neutrons to be absorbed in the section  $i$ .

Maximal external neutron source amplification in the sectioned reactor core can be achieved when the neutron coupling between booster and target is completely broken ( $k_{21} = 0$ ). In this case for the fissionable target with a reference source and  $k_{\text{eff}} = k_1 = k_2 = 0.98$ ,  $k_{\infty 1} = k_{\infty 2} = 2.1$  it could be obtained  $k_{\text{amp1}} = 27$ .

Neutron coupling between the booster and the target can be broken by several ways.

1. Cascade fast-thermal reactor core: the inner section is fast and the outer is thermal. The neutron coupling between booster and target is suppressed because of placing a “neutronics gate” (thermal neutrons absorber) between sections.

But in real systems it is impossible to break neutron coupling completely because there are neutrons with rather high energies in the outer section, which can't be absorbed in the “neutronics gate”. It should be noted that

during ADS operating there is a significant  $k_{\infty}$  changes due to fuel burnup and fission product build-up. This leads to  $k_{\text{eff}}$  significant decrease.

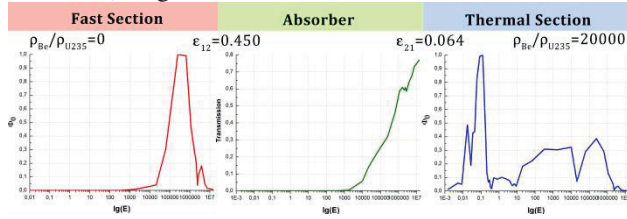


Figure 4: Neutrons energy spectrum in the fast-thermal sectioned reactor core and the gate capacity ( $B^{10}$ ).

2. Cascade reactor core with threshold fissionable target: the inner section consists of threshold fissile material, for example,  $\text{Np}^{237}$ , that allows to break neutron coupling more efficiently.

Transuranic threshold fissile elements are possible to utilize only in transmutation plants. Threshold fissile elements ( $\text{U}^{238}$ ) usage in energy plants isn't reasonable because in this case the fissionable target has a very low  $k_{\infty 1}$  value.

3. Fast-fast cascade reactor core: inner and outer section with hard spectrum divided by a cylindrical gap (this gap can be named “geometrical gap” for convenience). Neutron coupling between inner and outer sections is suppressed at the expense of the ratio of the total neutron flux in the inner section to the outer section is in proportion to  $R_1/R_2$  (in spherical case to  $R_1^2/R_2^2$ ) (Fig. 5).

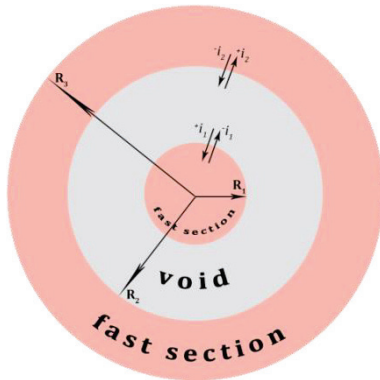


Figure 5: Fast-fast cascade reactor core scheme. 1 — inner section, 2 — void, 3 — outer section.

Cascade reactor cores have rather strong power flux irregularity between sections, because in some cases ADS power is limited not by the external neutron source intensity but an acceptable specific power flux in the reactor core, which is defined under the heat engineering reliability condition. The mentioned limitation is occurred for reactor cores with “geometrical gap”, when the fuel volume fraction is rather small and  $\text{U}^{235}$  enrichment in the fissionable target is greater than in the booster. In such reactor cores it is reasonable to use liquid metal coolant, that allows to increase maximal heat density up to  $1180 \text{ MW/m}^3$ .

Heat density distributions for homogenous and cascade reactor cores with power 250 MW are presented in Fig. 6.

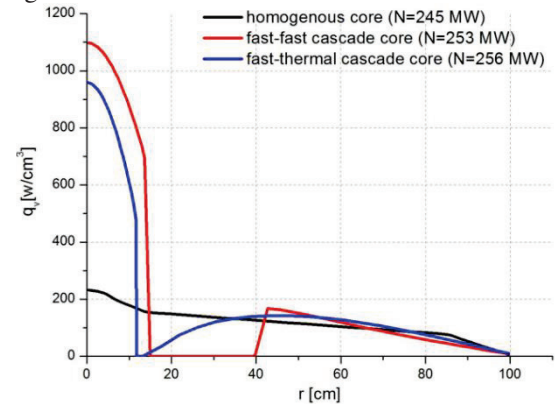


Figure 6: Dependence of heat density in the reactor core ( $R=100 \text{ cm}$ ).

Neutronics calculations results for initial neutrons yield in the fissionable target and low-energy accelerator (characteristics in Table 1), are presented in Table 2.

Table 2: Reactor core characteristics for its different types ( $k_{\text{eff}}=0.98$ )

	Traditi onal	Fast- Fast	Fast- Fast	Fast- Thermal
$q_v^{\text{max}}$ [MW/m <sup>3</sup> ]	232	1098	700	989
$k_1$	—	0.64	0.71	0.81
$k_2$	—	0.971	0.939	0.979
$k_{12}$	—	1.28	0.08	0.26
$k_{21}$	—	0.0952	0.0055	0.0053
$R$ [m]	1	1	2	1
$N$ [MW]	245	253	300	256

## CONCLUSION

ADSR with thermal power up to 300 MW could be created on the basis of the proton linac (Table 1), subcritical reactor with sectioned core (Table 2), cooled by liquid metal.

## REFERENCES

- [1] A.G. Golovkina, et al. “Project of Low-Energy Accelerator Driven Power Plant”, RuPAC’12, St. Petersburg, September 2012, p. 224-226 (2012).
- [2] Yu.A. Svistunov, et al. Characteristics of ADS Target Irradiated by 200...400 MeV // Problems of Atomic Science and Technology. N. 3, i. 91. 2014, p. 64–69.
- [3] A.G. Golovkina, et al. Power of ADS with low energy accelerator and fissionable target // Problems of Atomic Science and Technology. N. 4, i. 86. 2013, p. 328–332.