CHARACTERISTICS OF ADS TARGET IRRADIATED BY 200…400 MeV PROTON BEAM

Yu.A. Svistunov[1], I.V. Kudinovich[1], A.G. Golovkina[1], D.A. Ovsyannikov[1], A.A. Bogdanov[2], A.V. Tanchuk[3]
[1]Saint-Petersburg State University, St.-Petersburg, Russia
E-mail: svistunov@luts.niiefa.spb.su; golovkina.a@gmail.com; igor_kudinovich@mail.ru; dovs45@mail.ru;
[2]Krylov State Research Center, St.-Petersburg, Russia
E-mail: foyd1@rambler.ru;
[3]NIIEFA, St.-Petersburg, Russia

The problems of target choice for compact ADS with reactor thermal power 200…400 MW and 200…400 MeV proton beam are considered. Simulation results of neutron yield from fissile and non-fissile targets are presented and the optimal target sizes are calculated. The principal target design characteristics and its thermal condition are also considered.

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INTRODUCTION

Combination of high-power neutron sources with systems containing nuclear fuel, or so called hybrid systems, are being researched in various countries [1 - 4]. The neutrons excess in such systems can be used for the most of long-living radionuclides transformation into isotopes with far less decay times. In addition the subcritical condition in such hybrid systems also provides advantages from safety standpoint in comparison with regular critical nuclear reactors. A proton accelerator combined with a target can possibly be considered as the required neutron source. The development of a hybrid system requires additional research of all system components (accelerator, target, reactor etc.).

Nowadays projects of such hybrid systems are being considered with proton and deuteron beams accelerated mostly up to 1 to 2 GeV (for ex. [5 - 7]). This tendency is explained by the fact that the nuclear waste transmutation is considered to be the primary problem, although energy production is also considered. On the other hand, the development of 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 complex for the transmutation of long-living radioactive isotopes, would also be an interesting idea. Such power plant doesn't require a large accelerator and huge investment and can be created using modern accelerator and reactor technologies. Also accelerator parameters optimization is carried out [8 - 12] in order to improve nowadays accelerator characteristics.

1. NEUTRON GENERATION IN TARGETS OF DIFFERENT MATERIALS

The ADS target should provide the maximum neutron yield being irradiated 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.

It should be noted that amount of experimental data on neutron yield from targets irradiated by 200…400 MeV proton beam is much less than for targets irradiated by 0.6…1 GeV proton beams [13]. For neutron yield calculation the Geant 4.10 with enabled ENDF cross-section libraries was used. The verification results of QGSP_BIC_HP library [14] physical models are presented in the Table 1.

Table 1

Verification results of Geant physical models library with experimental data [15]

№	Target diameter D, cm	Target length L, cm	Target material density, g/cm^3	Proton energy Ep, MeV	Experiment		Geant 4.9.6p. 2 (10^5)
					Neutron yield N	±ΔN	QGSP_BIC_HP
1	20.4	61	^{238}U / 18.95	470	18.1	0.9	16.9
				720	29.1	1.5	30.6
				960	40.5	2	41.9
2	10.2	61	Pb / 11.35	470	8.0	0.4	7.4
				720	11.8	0.6	12.9
				960	16.6	0.8	17.1
3	10	60	Pb / 11.35	317	3,13	0.06	3.9
				470	6.4	0.3	7.5
				960	16.8	0.5	16.9
4	20.4	61	Pb / 11.35	470	8.7	0.4	8.3
				720	13.9	0.7	15.1
				960	20.3	1.1	20.8
5	10.2	61	Pb / 11.35 + $H_2$0 / 0.9982	540	9.0	0	8.9
				720	13.3	0	12.5
				960	17.7	0	16.9

As follows from Table 1 data, for calculation of ADS target irradiated by the 200…400 MeV proton beam the Geant physical models library QGSP_BIC_HP can be used.

The neutron generating targets can conditionally be divided into two categories [16]: 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 higher than in non-fissile targets: the fissile isotopes fission process makes an additional contribution to the sum energy release and neutron generation.

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.

For fissile ADS targets uranium based targets with different fuel compositions are considered.

In ADS with targets of non-fissile materials the external neutron source intensity is specified by the spallation neutrons leakage from the target surface. For small sized targets a significant part of secondary particles that can induce nuclear fissions leave the target. For large sized – radioactive capture of neutrons by the target plays an important role (Fig. 1).

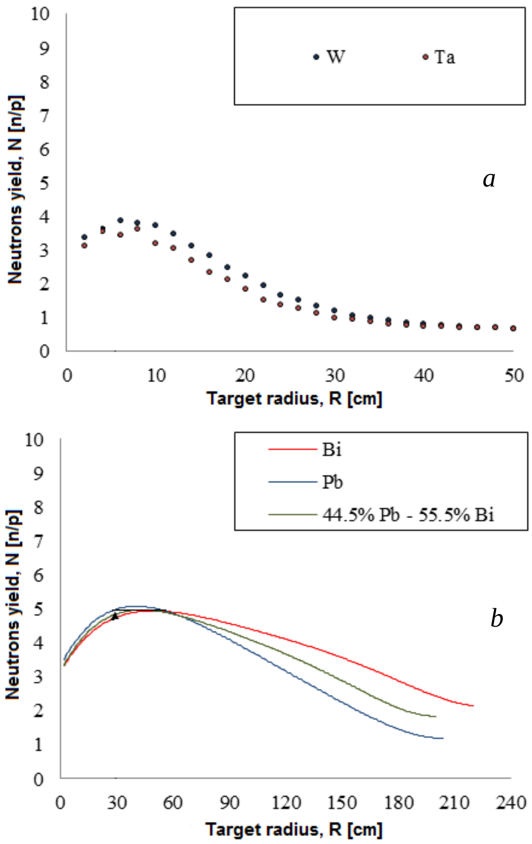

Fig. 1. Neutron yield from non-fissile (W, Ta (a); Bi,Pb,Bi+Pb (b)) cylindrical target surface with infinite length in dependence of its radius (E_p= 300 MeV)

Because of an anisotropy of non-elastic proton scattering the target length should in several times be greater than its radius, meanwhile the *L* value has weak influence on neutron yield if the following condition $L>D>\lambda_{in}$ is fulfilled. A great part of neutron leakage comes from the target face from the side of beam falling. So the neutron yield is maximal with some beam entry point deepening [17]. Beam entry point deepening also help to decrease the negative radiation effects on accelerator elements and the beam output facility.

The cylindrical targets optimal sizes irradiated by 300 MeV proton beam are presented in the Table 2.The neutron yield of these targets with proton 200…400 MeV is presented in Fig. 2.

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	E_p=300 MeV			
	D_{opt}, cm	L_{opt}, cm	Z_{opt}, 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

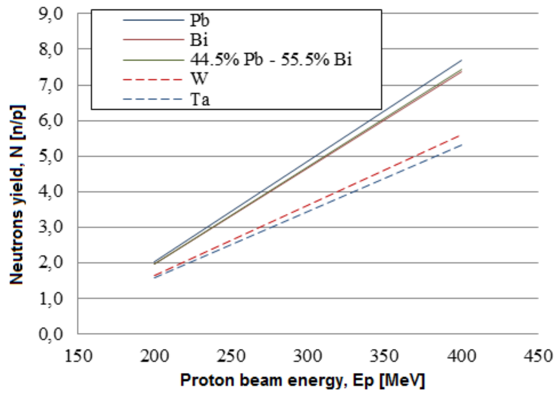

Fig. 2. Neutron yield from the non-fissile cylindrical target surface with optimal sizes (E_p = 200…400 MeV)

In ADS with non-fissile targets the initial neutrons born in spallation reactions are multiplied because of the fission process in the target.

Calculation results of the total neutrons yield from ^{238}U cylindrical targets of different radiuses are presented in Fig. 3. As the Fig. 3 indicates the total neutrons yield reaches the value 13 n/p in uranium target with an optimal radius *r* = 30 cm (E_p=300 MeV).

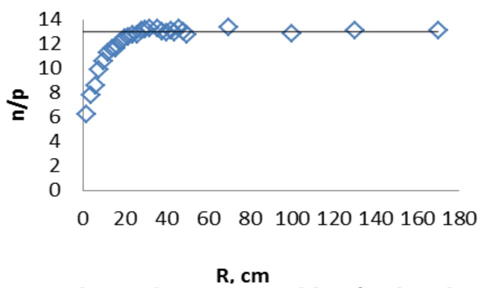

Fig. 3. The total neutrons yield in fissile cylindrical target (^{238}U) with infinite length in dependence of its radius (E_p= 300 MeV)

A proton accelerator with the following characteristics: E_p = 300 MeV, I_p = 5 mA is proposed to be used for ADS with thermal power 200…400 MW. In this case the neutrons source intensity from tantalum target is
$S_0 \approx 10^{17}$ n/s, and from uranium target – $S_0 \approx 4{\cdot}10^{17}$ n/s.

2. PRINCIPAL DESIGN CHARACTERISTICS FOR ADS TARGET

Two target alternatives for ADS with thermal power 200…400 MW are considered in this paper.

The construction with fuel elements is considered as a fissile target (Fig. 4) [18].

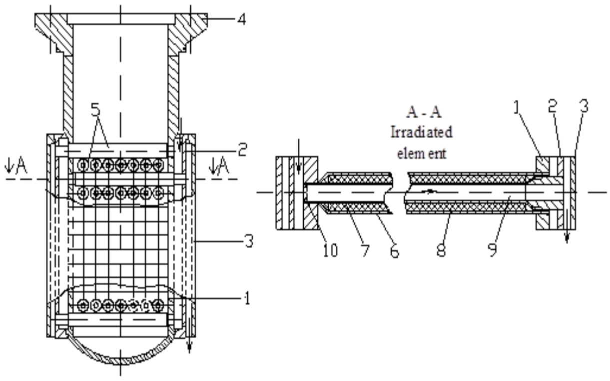

Fig. 4. Neutrons generating target: 1, 2, 3 – vessel with channels for coolant; 4 – vacuum ion guide; 5 – irradiated elements; 6, 7 – shells of irradiated element; 8 – fissile material; 9 – coolant channel; 10 – throttle

The target shell consists of three coaxial shells. The inner shell is hermetically sealed onto the beam canal. The inner shell also contains the irradiated tubes. Thus, the inner part of the shell, which is connected to the beam canal, is sealed and isolated from the coolant and contains vacuum/evacuated. Heat withdrawal from the target located inside the reactor is fulfilled via reactor coolant (Helium). The outer and middle shells of the target serve as a circulation system for the coolant. The middle shell has holes in its side to which all the irradiated tubes of the inner shell are connected individually. Empty spaces between the inner and the middle shell, and the middle and the outer shell form the pressure and draining manifolds for the coolant of the neutron target.

Each irradiated element consists of two thin coaxial tubes. Between these tubes lies the neutron producing material. This design of the irradiated elements allows any form of neutron producing material to be used (powder, liquid, tablet etc.) and lowers the requirement for its radiation and thermal resistance.

An orifice is installed into the inner tubes of every irradiated element to help maintain a defined flow of the coolant. Rows of irradiated tubes are placed in layers with each layer containing tubes facing one direction. This stiffens the inner shell, which is constantly under external pressure from the coolant. The density and composition of the neutron material may vary from layer to layer to help maintain a required rate of neutron generation along the length of the target.

The principle design of non-fissile neutron generating target is presented in the Fig. 5.

3. ENERGY RELEASE IN THE ADS TARGET

Energy release in the ADS target, situated in the reactor core is conditioned as straight by irradiation by high-energy charged particles, as by heat generation because of neutron and gamma radiation in the reactor core.

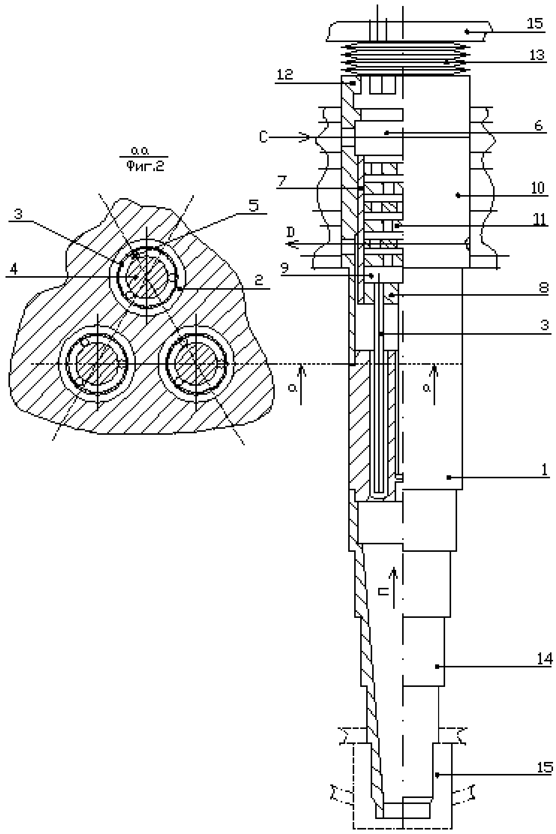

Fig. 5. Neutrons generating target design: 1 – beam guid; 2 – the target main array; 3 – tube plate; 4 – protection screens; 5 – pressure header shell; 6 – target flange; 7 – outer shell; 8 – cooling channels; 9 – wire coiling; 10 – tube; 11 – tube core

In the general case heat generation in the target induced by charged particles beam is specified by charged particles ionization losses (charged particles electromagnetic interactions with the matter), cascade hadron inelastic interactions (neutrons, protons, π-mesons) with the target matter nucleus, target matter nucleus fission process. In principle, energy release in the target can exceed the energy of the proton beam coming from the accelerator because of energy, released in fission and elementary particles secession from the nucleus. In order to evaluate the energy release value in the target irradiated by proton beam in this paper we use some calculation data from [15, 19] and experimental data from [20].

As follows from the data presented in [15] the heat generation power level, released in the target irradiated by proton beam (Q_P), is connected with beam power N_P (with E_p = 400 MeV):

for tantalum $Q_P = 0.7\, N_p$;

for uranium $Q_P = 1.2\, N_p$,

where $N_p = E_p\, I_p$, MeV.

The energy release in the target irradiated by narrow charged particles beam has significant space irregularity

$q_p(r, z)$. Specific energy release is maximal along the beam entrance line $q_{p0}(z)$, (r= 0, z – coordinate in the target counted from the beam entrance point, cm). In [20] from the experimental data analysis the following expression was obtained:

$$q_{P0}(z) = q_{p0}^{0} \exp(-1.43 z / \lambda_{in}).$$

The maximal specific energy release $q_{P_0}^{0}$ is located in the beam entrance point. Some calculation results are presented in [19], from which it follows that the maximal volume heat intensity $q_{P_0}^{0}$ in uranium target, E = 500 MeV and the average proton current density in the beam entrance point of the target 0.01 mA/cm^2 reaches the value up to 100 MW/m^3. The acceptable heat intensity in the target is conditioned by the maximal allowable target matter temperature, which is defined within thermal design.

Radiation heat generation value in the target, situated inside the reactor core, is specified the same way as heat generation value in the structural materials of the reactor core [21].

Specific energy release conditioned by gamma radiation is calculated using the following formula:

$$q_\gamma(\vec{r}) = \int_{E_T} \Phi_\gamma(E, \vec{r}) \cdot \mu_{\gamma a}(E_\gamma) dE ,$$

where Φ_γ is space-energy gamma-radiation flux density distribution;

μ_{Ta} – energy of gamma-radiation linear absorption coefficient in the target material.

Integral energy release value in the target conditioned by gamma radiation is defined by the formula:

$$Q_\gamma = \int_V q_\gamma(\vec{r}) dV .$$

Specific energy release, conditioned by neutron slowdown in the target matter is described by this formula:

$$q_n(\vec{r}) = \xi \int_{\ddot{E}}^{E_f} \Sigma_S(E) E_n \Phi_n(r, E) dE ,$$

where ξ – neutron average logarithmic energy loss in elastic scattering process; Σ_S – macroscopic scattering cross-section; Φ_n – space-energy neutron flux density distribution.

Integral energy release value conditioned by the neutron slowdown process is defined by the formula:

$$Q_n = \int_V q_n(\vec{r}) dV.$$

Let us consider the thermal condition of the non-fissile tantalum target (see Fig. 5), irradiated by the proton beam with energy E_p = 400 MeV and average current I_p=5 mA as an example. Calculations were carried out for ADS based on the gas-cooled reactor with thermal power level 200 and 400 MW. The total energy release power level in the tantalum target is about 1.46 MW, though the energy release power level, conditioned by protons is about 1.4 MW, energy release power level, conditioned by gamma radiation is about 0.06 MW, also energy release conditioned by the neutron slowdown process can be neglected. The distribution of specific energy release power level along the target axis is presented in the Fig. 6 [22].

The target embodiment allows to consider it as a heat generating array of cylindrical shape, penetrated by 463 axial cooling channels. These channels are treated as Fiels-tubes, situated in the triangle lattice (Fig. 7).

The target is cooled by the reactor primary coolant circuit, so the gas coolant (Helium) pressure in the target is about P = 10 MPa, and the temperature in the target entrance point 300°C (before the moment when the coolant reaches the target, it cools structural componentry in the reactor). The target coolant (Helium) temperature is assumed to reach 600°C in the output. This fact allows to provide quite high mechanical properties in structural materials, influenced by coolant pressure (degasified channel, bringing particle beam to the target).

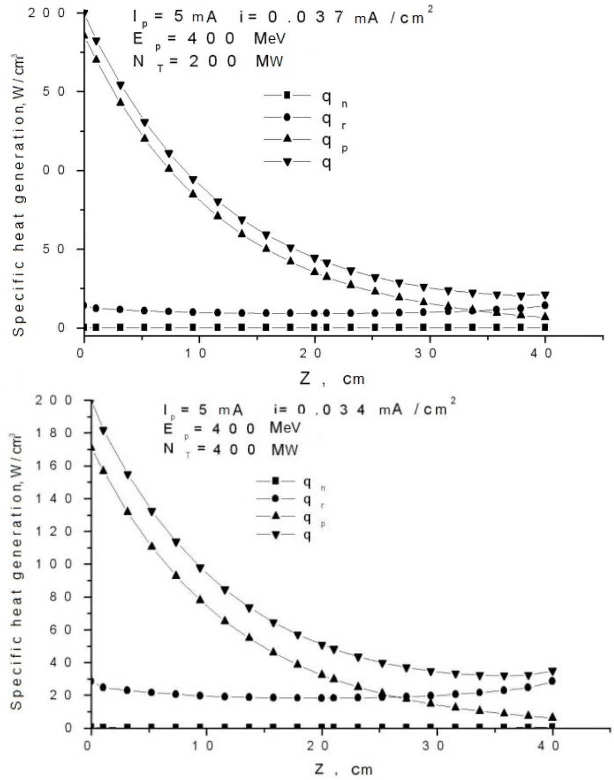

Fig. 6. Distribution of specific energy release power level along the target axis

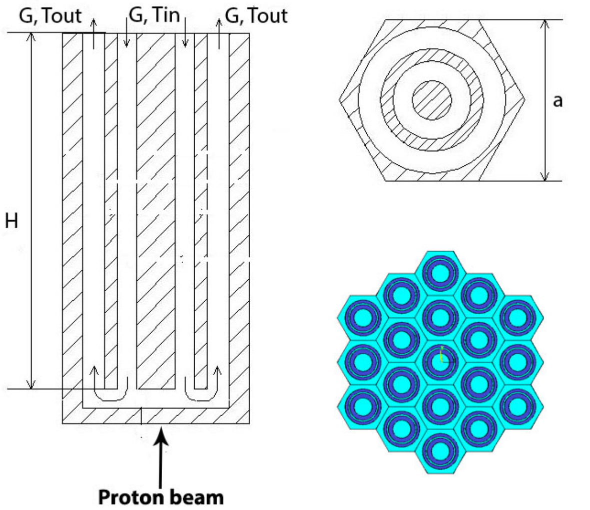

Fig. 7. A target cell scheme and the central cells cluster, situated over the entrance channel, configuration channels

Some statements follow from the target thermal calculations performed via ANSYS (Figs. 8, 9):

– target material temperature along the coolant circuit doesn't exceed 900°C;

– maximal temperature of target material reaches 2000°C in the target central cell bottom.

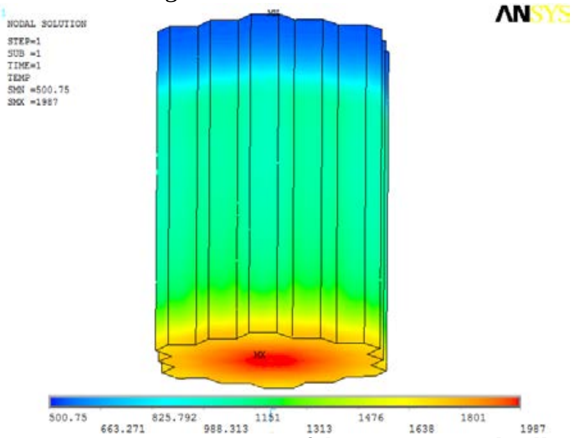

Fig. 8. Temperature state of the target central cells cluster(outer surface), °C

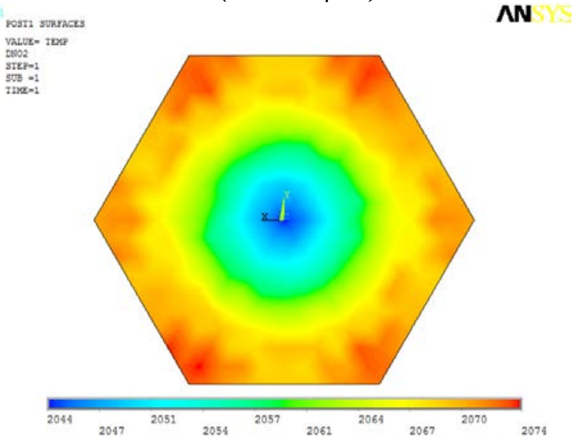

Fig. 9. Temperature distribution in the target bottom element (central cell)

CONCLUSIONS

Non-fissile materials, made of high-melting metals (Ta or W), can be used as targets for ADS with power level 200…400 MW and the following proton beam characteristics: E_p = 200…400 MeV, I_p=5 mA. The neutron generation intensity in such targets can reach $S_0 \approx 10^{17}$ n/s. Also fissile targets, performed as a fuel elements set, are good as well for ADS purposes. The total neutron generation intensity in them is about $S_0 \approx 4 \cdot 10^{17}$ n/s.

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REFERENCES

1. H. Aït Abderrahim, P. Kupschus, Ph. Benoit, et al. MYRRHA, a multipurpose accelerator-driven system for R&D pre-design study completion // *Proc. of 7-th Information Exchange Meeting on Actinide and Fission Product Portioning and Transmutation*. Jeju, Korea. 2002, p. 899-908.
2. J.U. Knebel, H.A. Abderrahim, L. Cinotti, et al. EUROTRANS: European Research Programme for the Transmutation of High Level Nuclear Waste in an Accelerator Driven System // *Proc. of 9-th Nuclear Energy Information Exchange Meeting on Actinide and Fission Products Partitioning & Transmutation*. Nimes, France. 2006.
3. H.E. Thyebault1, P. Baeten, A. Billebaud, et al. The GUINEVERE Experiment: first PNS measurements in a lead moderated sub-critical fast core // *Proc. of International Congress on the Advances in Nuclear Power Plants (ICAPP'12)*, Chicago. 2012.
4. M.I. Ayzatskiy, B.V. Borts, A.N. Vodin, et al. NSC KIPT neutron source // *Problems of Atomic Science and Technology*. 2012, № 3, p. 3-9.
5. Y. Kuriyama et al. Status and Development of a proton FFAG Accelerator at KURRI for ADSR Study // *Proc. of PAC*. New York, NY, USA. 2011, p. 2172-2174.
6. D. De Bruyn et al. *Int. Workshop on Technology and Component of Accelerator Driven System*, Karlsruhe. 2010, OECD-NEA (2011), p. 47.
7. D. Vandeplassche and L. Medeiros, Romao Accelerator Driven System // *Proc. of IPAC*, New Orleans, USA. 2012, p. 6-10.
8. Yu.A. Svistunov, Yu.V. Zuev, A.D. Ovsyannikov, D.A. Ovsyannikov. Compact deuteron accelerator design for 1 MeV neutron source // *Vestnik St.-Petersburg University. Ser. 10*. 2011, iss. 1, p. 49-59 (in Russian).
9. A.D. Ovsyannikov, D.A. Ovsyannikov, S.-L. Chung. Optimization of a radial matching section // *International Journal of Modern Physics A*. 2009, v. 24, №5, p. 952-958.
10. D.A. Ovsyannikov, A.D. Ovsyannikov, I.V. Antropov, V.A. Kozynchenko. BDO-RFQ code and optimizationmodels // *Proc. of Physcon*. 2005, p. 282-288.
11. D.A. Ovsyannikov, A.D. Ovsyannikov, M.F. Vorogushin, Yu.A. Svistunov, A.P. Durkin. Beam dynamics optimization: models, methods and applications // *Nuclear Instruments and Methods in Physics Research. Section A*. 2006, v. 558, № 1, p. 11.
12. B. Bondarev, A. Durkin, Y. Ivanov, et al. The LIDOS.RRQ designer development // *Proc. of the IEEE Particle Accelerator Conference*, Chicago. 2001, p. 2947-2949.
13. A. Krasa, V. Wagner, M. Majerle, et al. Neutron production in a Pb/U-setup irradiated with 0.7…2.5 GeV protons and deuterons // *Nuclear Instruments and Methods in Physics Research. Section A*. 2010, v. 615, p. 70-77.
14. S. Agostinelli, J. Allison, K. Amako et al. Geant4 – a simulation toolkit // *Nuclear Instruments and Methods in Physics Research. Section A*. 2003, v. 506, iss. 3, p. 250-303.
15. V.S. Barashenkov. Nucleo-physical Aspects of the Electronuclear Method // *Physics of Particles and Nuclei*. 1978, v. 9, p. 871.
16. A.G. Golovkina, A.A. Bogdanov, I.V. Kudinovich, et al. Project of Low-Energy Accelerator Driven Power Plant // *Proc. of RuPAC*. St.-Petersburg, Russia. 2012, p. 224-226.
17. A.G. Golovkina, I.V. Kudinovich, D.A. Ovsyannikov. Power of ADS with low energy accelerator and fissionable target // *Problems of Atomic Science and Technology*. 2013, №4, iss. 86, p. 328-332.

18. L.N. Gerasimov, I.V. Kudinovich, Yu.A. Svistunov, V.P. Struev. Small-size accelerator driven nuclear power plant: Feasible technologic failures // *Izvestiya Akademii Nauk. Energetika*. 2005, № 2, p. 3-16, (in Russian).
19. Yu.M. Ado, V.P. Kryuchkov, V.N. Lebedev. Power subcritical nuclear reactor with beam of accelerated protons // *Atomnaya Energiya*. 1994, v. 77, iss. 4, p. 300-308, (in Russian).
20. V.I. Belyakov-Bodin. Heat deposition in targets bombarded by medium-energy protons // *Nuclear Instruments and Methods in Physics Research. Section A*. 1993, v. 335, iss.1-2, p. 30-36.
21. V.E. Glushkov, V.E. Demin, N.N. Ponomarev-Stepnoy, et al. *Heat generation in the reactor*. M.: „Energoatomizdat", 1985.
22. L.N. Gerasimov, I.V. Kudinovich, Yu.A. Svistunov. Tantalum neutron producing target // *Transactions of Krylov State Research Center*. 2005, №22, p. 109-120.

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ХАРАКТЕРИСТИКИ МИШЕНИ ЭЛЕКТРОЯДЕРНОЙ УСТАНОВКИ, ОБЛУЧАЕМОЙ ПУЧКОМ ПРОТОНОВ С ЭНЕРГИЕЙ 200…400 МэВ

Ю.А. Свистунов, И.В. Кудинович, А.Г. Головкина, Д.А. Овсянников, А.А. Богданов, А.В. Танчук

Рассмотрены вопросы выбора мишени для компактной электроядерной установки с мощностью реактора 200…400 МВт и энергией протонов 200…400 МэВ. Представлены результаты моделирования выходов нейтронов из размножающих и неразмножающих мишеней и определены оптимальные размеры мишени. Рассмотрены особенности конструкции мишени и вопросы ее температурного состояния.

ХАРАКТЕРИСТИКИ МІШЕНІ ЕЛЕКТРОЯДЕРНОЇ УСТАНОВКИ, ЩО ОПРОМІНЮЄТЬСЯ ПУЧКОМ ПРОТОНІВ З ЕНЕРГІЄЮ 200…400 МеВ

Ю.А. Свистунов, І.В. Кудинович, А.Г. Головкіна, Д.О. Овсянников, А.А. Богданов, А.В. Танчук

Розглянуто питання вибору мішені для компактної електроядерної установки з потужністю реактора 200…400 МВт і енергією протонів 200…400 МеВ. Представлено результати моделювання виходів нейтронів із розмножуючих і нерозмножуючих мішеней та визначені оптимальні розміри мішені. Розглянуто особливості конструкції мішені і питання її температурного стану.