STUDY OF ONE-ZONE SUBCRITICAL AMPLIFIERS OF NEUTRON FLUX INVOLVING ENRICHED URANIUM

***V.A. Babenko*[1], *V.I. Gulik*[2], *L.L. Jenkovszky*[1], *V.N. Pavlovich*[2], *E.A. Pupirina*[3]**

[1]*Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev*
e-mail: pet@online.com.ua, jenk@gluk.org
[2]*Institute for Nuclear Research, National Academy of Sciences of Ukraine, Kiev*
e-mail: gulik@kinr.kiev.ua, pavlovich@kinr.kiev.ua
[3]*National Taras Shevchenko University, Kiev*
e-mail: pulen@univ.kiev.ua

We examine the main aspects of the construction of subcritical systems able to multiply neutrons from the external source with emphasis on the choice of the neutron source and optimization of the parameters of the subcritical system. We present results of our calculations of neutron flux amplification factor for the one-zone spherical systems made up of the enriched uranium, water solution of the enriched uranium, and for the spherical enriched uranium system with reflector.

PACS: 12.20.-m, 13.40.-f, 13.60-Hb, 13.88.+e

1. INTRODUCTION

Studies of different authors [1-3] show that the construction of accelerator-driven subcritical systems is a very promising way in nuclear power engineering. Such systems provide a possibility to improve the safety level and to work out effective methods of transmutation of long-lived radioactive waste.

Here we present further development of our previous work [4]. The theoretic background of the development of accelerator-driven subcritical systems can be found in more detail in [4], as well as preliminary results of our studies.

We investigate the amplification of the neutron flux by a number of subcritical systems, namely, by a homogeneous spherical assembly made up of enriched uranium, by a homogeneous spherical assembly made up of water solution of enriched uranium, and by a homogeneous spherical assembly made up of enriched uranium and containing beryllium reflector..

2. DESCRIPTION OF SYSTEMS UNDER CONSIDERATION

The main objective of our investigation is to establish basic laws of the behavior of the amplification factors of neutron flux and energy depending on primary features of the assembly - such as nuclide composition, energy of neutrons of the external source, effective multiplication factor of the system, ratio of nuclear concentrations. Study of such model assemblies is of interest for a better understanding of amplification properties of more complicated systems and for optimization their parameters. Even such simple systems show a number of nontrivial properties concerning amplification of neutron flux, in particular amplification factors have nonmonotonic behavior depending on the uranium enrichment and ratio of nuclear concentrations (H/U). We choose physical systems to be slightly subcritical, namely, we fix the value of neutron effective multiplication factor of each system to be equal k_{eff}=0.99.

We consider a point isotropic source of neutrons with energy of 14 MeV to be the "external" source, which is located at the centre of spherical subcritical assembly. Actually, realistic neutron sources from D-T reactions are neither isotropic nor monoenergetic, however the simplified model we use is rather typical and it is frequently used. The geometric dimension (radius) of the assembly is fixed by the requirement for the effective multiplication factor of the system to be equal to a certain specified value, which is slightly less than unity, i.e. the assembly should be slightly subcritical. Calculations of the amplification factors and other physical characteristics of the systems under consideration were done with the help of the neutron Monte Carlo transport code MCNP-4C [5], which employs the latest ENDF/B-VI nuclear data library.

Two reasons determine our choice of neutron source energy to be equal 14 MeV. 1. Today we have two possibilities to obtain neutrons via the process of interaction of accelerated charged particles with matter, namely, with the help of D-T reaction and with the help of spallation process. Spallation reaction gives neutrons as a result of the interaction of fast charged particles (for example, protons with energy ~1 GeV) with nuclei of heavy metals (for example, with mixture of lead and bismuth) [6]. Fusion reaction may be accomplished with the help of deuteron accelerators working at energy 100…200 keV and currents ~ ampere. Such a current is capable to yield a neutron flux, which is equivalent to the neutron flux produced by proton accelerators with energy ~1 GeV and current ~ mA. At the same time a project based on D-T reaction costs a few times less than the one based on spallation. 2. Spallation neutrons have a rather wide energy spectrum with the maximum lying at 200…300 MeV. Neutron cross-sections in this region, however, are not known sufficiently well and they are not available for all nuclides needed. Since relevant cross-section libraries in this energy range are missing, calculation with the neutron source from spallation process is problematic. At the same time the neutron source with the energy of 14 MeV, resulting from D-T reaction, is available technically, while the neutron cross-sections in this energy range are well known and they are collected in corresponding libraries. In this connection, it is important to study efficiency of transmutation with the "14-MeV neutrons" and to compare results with those, obtained with "spallation neutrons".

3. RESULTS OF CALCULATIONS

The first system under consideration will be a one-zone homogeneous spherical assembly made up of the enriched uranium. We fix the value of the neutron effective multiplication factor of the system to be equal k_{eff}=0.99. Variation of the uranium enrichment w in the isotope ^{235}U, at fixed value of k_{eff}, results in variation of the assembly radius R. To be more specific, the decrease of the uranium enrichment leads to the decrease of multiplication factor of an infinite medium k_∞, and hence the radius of the system should increase in order to keep constant value of k_{eff}=0.99.

As already mentioned, we consider an external source of neutrons to be pointlike, isotropic and monoenergetic with the energy E_0=14 MeV. It is located at the centre of a spherical assembly. We define the flux amplification factor q as the ratio of the total number of neutrons passing through the external boundary surface in a time unit, N_S, to the intensity of the neutron source I_0, i.e. to the number of neutrons emitted by the source in a time unit: $q=N_S/I_0$. It will be convenient to choose the intensity of the neutron source to be equal to unity, I_0=1 n/sec, i.e. our results are normalized to be per starting single neutron from the source. The amplification factors, obviously, does not depend on the normalization. We define the energy amplification factor G as the ratio of the total energy deposition in the system to the source energy E_0.

We study the dependence of the flux amplification factor q and the energy amplification factor G on the uranium enrichment w_{U235} for the system under consideration. The results of our calculations are presented in Table 1. In the same table we give the calculated values of the multiplication factor of an infinite medium k_∞, of the radius of the assembly R, of the mean neutron flux in the volume $\overline{\Phi}$, and of the neutron flux through the external boundary of the system Φ_S. We also present the values of the fission density ρ_{fis} (which means the number of fissions per volume unit), and the total number of fissions in the system N_{fis}.

Table 1. *Physical properties of one-zone spherical amplifier of neutron flux, which is made up of the enriched uranium, as functions of the uranium enrichment*

w_{U235}, %	k_∞	R, cm	$\overline{\Phi}$, n/cm^2·sec	ΦS, n/cm^2·sec	ρfis, 1/cm^3·sec	Nfis, 1/sec	G	q
6	1.07	85.81	$4.99\cdot10^{-3}$	$2.29\cdot10^{-4}$	$2.89\cdot10^{-5}$	76.46	988.61	21.19
7	1.18	56.38	$1.59\cdot10^{-2}$	$1.23\cdot10^{-3}$	$1.04\cdot10^{-4}$	78.42	1013.94	49.03
8	1.26	45.34	$2.74\cdot10^{-2}$	$2.69\cdot10^{-3}$	$2.02\cdot10^{-4}$	78.72	1017.79	69.50
9	1.34	39.13	$3.83\cdot10^{-2}$	$4.38\cdot10^{-3}$	$3.11\cdot10^{-4}$	78.19	1010.89	84.38
10	1.41	35.05	$4.82\cdot10^{-2}$	$6.17\cdot10^{-3}$	$4.28\cdot10^{-4}$	78.33	996.54	95.12
20	1.82	20.81	$1.15\cdot10^{-1}$	$2.39\cdot10^{-2}$	$1.83\cdot10^{-3}$	77.08	892.29	130.34
30	2.01	16.38	$1.59\cdot10^{-1}$	$4.00\cdot10^{-2}$	$3.53\cdot10^{-3}$	64.85	838.16	135.01
40	2.12	13.93	$2.00\cdot10^{-1}$	$5.68\cdot10^{-2}$	$5.63\cdot10^{-3}$	63.81	824.67	138.53
50	2.20	12.32	$2.45\cdot10^{-1}$	$7.55\cdot10^{-2}$	$8.28\cdot10^{-3}$	64.77	837.09	143.81
60	2.25	11.13	$2.93\cdot10^{-1}$	$9.62\cdot10^{-2}$	$1.15\cdot10^{-2}$	66.60	860.60	149.86
70	2.29	10.22	$3.46\cdot10^{-1}$	$1.19\cdot10^{-1}$	$1.54\cdot10^{-2}$	68.96	891.14	156.54
80	2.32	9.49	$4.12\cdot10^{-1}$	$1.48\cdot10^{-1}$	$2.05\cdot10^{-2}$	73.30	947.15	167.36
90	2.35	8.88	$4.76\cdot10^{-1}$	$1.77\cdot10^{-1}$	$2.61\cdot10^{-2}$	76.42	987.39	175.19
100	2.37	8.36	$5.67\cdot10^{-1}$	$2.17\cdot10^{-1}$	$3.38\cdot10^{-2}$	82.92	1071.31	190.52

The main features of the system were found to be the following. One observes that the flux amplification factor q depends monotonically on the enrichment and it increases with the increase of the enrichment. At the same time the energy amplification factor G depending on the enrichment decreases, reaching a minimum, then rising again (see Table 1). To study this phenomenon we have calculated also the fission density and the total number of fissions in the system (see Table 1). The fission density monotonically increases with the growth of the enrichment, while the total number of fissions has the same dependence on the enrichment as the energy amplification factor G. Such a behavior may be explained as follows. Inasmuch as we fix the neutron effective multiplication factor, we have a large volume of the system at low enrichment and most of neutrons have time to be absorbed. By increasing the enrichment, the dimensions of the system decrease and part of the neutrons simply don't have time to interact with uranium. Data presented in Table 2 also support this phenomenon. Here L_{tot} is a total mean free path of neutrons in the medium, L_{fis} is the mean free path before the fission. As a result, we come to the following conclusion - the maximal amplification factor will appear in the system with dimensions exceeding the neutron mean free path before the fission ($1/\Sigma_{fis}$).

Table 2. *Total mean free path of neutrons in the medium and mean free path before the fission as functions of the uranium enrichment for the one-zone homogeneous spherical assembly made up of the enriched uranium*

w_{U235}, %	R, cm	L_{tot}, cm	L_{fis}, cm	L_{fis}/R
6	85.81	2.04	172.71	2.01
7	56.38	2.07	151.75	2.69
8	45.34	2.09	135.65	2.99
9	39.13	2.12	122.88	3.14
10	35.05	2.14	112.49	3.21
20	20.81	2.27	63.00	3.03
30	16.37	2.35	44.99	2.75
40	13.93	2.40	35.48	2.55
50	12.31	2.45	29.54	2.40
60	11.13	2.48	25.44	2.29
70	10.22	2.50	22.43	2.19
80	9.49	2.53	20.12	2.12
90	8.88	2.55	18.27	2.06
100	8.36	2.56	16.76	2.00

It should be noted that while the flux amplification factor q is falling slowly in the range of the enrichment between 100 and 20 percents, it starts decreasing drastically below w<20%. So, it is advantageous to choose enrichment of the system to be slightly greater than 20%.

In a similar manner, we consider one-zone spherical assembly involving water solution of the enriched uranium. At fixed value of k_{eff}=0.99, radius of the assembly R will change depending on the ratio of nuclear concentrations of the moderator (hydrogen) and the fuel (uranium) - H/U. The main parameters necessary for calculations were determined similarly to the first system.

We have calculated the flux amplification factor q and the energy amplification factor G depending on the ratio of nuclear concentrations H/U, sometimes called "moderation parameter". The results of calculations are presented in Table 3. We also give the values of radius of the system R, the volume of the system V, the mean free path of the neutron L_{tot}, and the neutron mean free path before the fission L_{fis}.

Table 3. *Amplification factors and other physical characteristics as functions of moderation parameter for the one-zone spherical assembly involving water solution of the enriched uranium*

H/U	0.0001	8.377	G	L_{fis}, cm	L_{tot}, cm
		171.233	960.27	16.845	2.577
0.0005	8.382	171.744	962.75	16.851	2.576
0.001	8.388	168.829	947.25	16.850	2.576
0.005	8.401	176.63	991.02	16.89	2.573
0.01	8.414	172.063	967.35	16.92	2.568
0.05	8.553	180.124	1018.07	17.22	2.532
0.1	8.708	192.501	1095.58	17.57	2.488
0.5	9.691	275.874	1652.21	19.55	2.197
0.6	9.88	290.293	1757.17	19.91	2.143
0.7	10.059	307.437	1881.04	20.23	2.093
0.8	10.225	313.898	1939.29	20.53	2.049
0.9	10.38	361.468	2253.7	20.80	2.001
1	10.528	348.202	2188.84	21.06	1.973
2	11.622	419.654	2814.51	22.95	1.735
3	12.315	348.351	2426.22	24.20	1.612
4	12.782	223.486	1591.14	25.11	1.536
5	13.109	172.75	1245.62	25.84	1.483
10	13.831	89.805	659.08	27.98	1.351
15	14.043	53.260	385.88	29.22	1.294
20	14.128	46.24	331.71	30.10	1.259
25	14.174	43.227	308.23	30.66	1.231
30	14.206	31.549	221.47	31.42	1.219
35	14.236	26.085	180.82	32.06	1.207
40	14.263	27.074	187.19	32.45	1.191
45	14.293	24.409	167.58	32.92	1.180
50	14.328	23.153	158.4	33.32	1.170
100	14.658	12.995	85.07	37.25	1.110
200	15.545	9.717	63.46	43.02	1.024
300	16.465	8.371	55.90	47.91	0.963
400	17.435	7.248	49.82	52.84	0.921
500	18.455	7.135	51.28	57.50	0.881
600	19.558	7.006	53.20	61.16	0.849
700	20.718	6.880	55.35	65.16	0.822
800	22.008	6.851	58.95	69.04	0.798
900	23.375	7.086	66.08	72.50	0.776
1000	24.925	6.917	69.81	76.39	0.760

The main features of this system were found to be the following. The dependence of the flux amplification factor q on the ratio of nuclear concentrations H/U shows a nonmonotonic behaviour. At first, as the moderation parameter H/U increases, q starts increasing very slowly, but then it has a stepwise jump at the value of moderation parameter H/U=0.5. Subsequently q increases and reaches a maximum at H/U=2…3, whereupon it starts decreasing. This dependence also has stepwise jumps at the values H/U = 15 and H/U = 50. Thus, the dependence of the flux amplification factor on the moderation parameter has a pronounced maximum at H/U=2…3. This result may be used to construct more efficient systems. The energy amplification factor G has similar dependence on the moderation parameter H/U with the only difference that there is a minimum at H/U=500, whereupon there is a slight increasing.

We have also calculated the properties of the subcritical system with a reflector. The spherical system under consideration is made up of the core involving enriched uranium and beryllium reflector of 50 cm thickness. The parameters of the system were chosen similarly to the previous cases to achieve the fixed value of neutron effective multiplication factor k_{eff}=0.99.

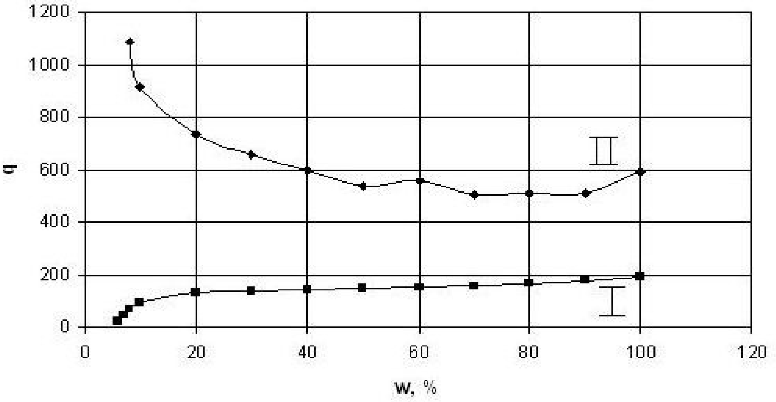

Fig. 1. *The neutron flux amplification factor versus the uranium enrichment. I - system without a reflector, II - system with beryllium reflector*

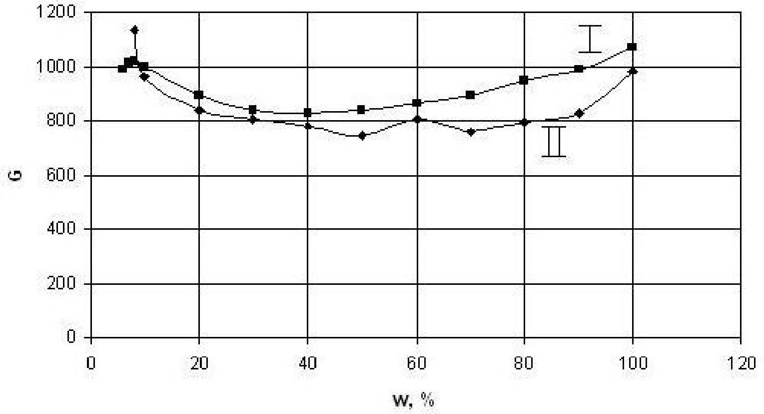

Fig. 2. *The energy amplification factor versus the uranium enrichment. I - system without a reflector, II - system with beryllium reflector*

The increase of the flux amplification factor q comprises a value of 3…5 times for the system with beryllium reflector. At the same time the nature of the q-dependence on the enrichment also changes (Fig. 1). As to the energy amplification factor G, it does not change neither by magnitude, nor by the character of its dependence (Fig. 2). The last fact is due to decrease of the fission volume of the system with a reflector at fixed value of k_{eff}=0.99.

4. CONCLUSION

Thus, even a very simple one-zone subcritical system allows one to obtain neutron flux amplification by 1 to 2 orders and energy amplification by 2 to 3 orders. An interesting result is that relatively low enrichments (10%…20%) yield energy amplifications close to those at high enrichment, which is very advantageous from the economical point of view. The flux amplification factor varies insignificantly in the interval of enrichments between 20% and 40%, but drastically decreases at smaller enrichments. Hence a system of a 20% enrichment in uranium-235 can serve as a reasonable amplifier both in flux and energy.

Subcritical system involving water solution of uranium-235 enables one to obtain better values of amplification factors in comparison with the system made up of metallic uranium. These values amount up to q=420 for the flux amplification factor, and G=2800 for the energy amplification factor.

A system with a reflector allows increasing the flux amplification factor as great as 3…5 times compared with a similar system without a reflector. The flux amplification factor reaches the value q=500…900 in this case, and the energy amplification factor reaches the value G=800…1000.

The enhancement of amplification factors of subcritical neutron-multiplying systems is not exhausted by the pursued research. The characteristics of more advanced multi-zone systems, as well as the possibility to use alternative fissile materials will be studied in the future. In particular, two-zone systems are of great interest since the utilization of a booster involving a material with $k_\infty>1$ makes it possible to increase the amplification factor significantly [7]. However, even the present stage of the study shows that subcritical neutron-multiplying assemblies are promising alternatives to the reactors as powerful sources of neutrons, suggesting various applications in nuclear physics and nuclear power engineering.

REFERENCES

1. C. Rubia et al. *Conceptual Design of a Fast Neutron Operated High Energy Amplifier* // CERN/AT/95–44(ET), 1995.
2. C.D. Bowman. Accelerator driven system for nuclear waste transmutation // *Ann. Rev. Nucl. Part. Sci.* 1998, v. 48, p. 505-556.
3. Seiji Shiroya, Hironobu Unesaki, Yohichi Kawase, Hirotake Moriyama, Makoto Inoue. *Basic Study on Nuclear Characteristics of Accelerator Driven Subcritical Reactor as Future Neutron Source*. Research Reactor University. 2001.
4. V.A. Babenko, L.L. Jenkovsky, V.N. Pavlovich, E.A. Pupirina On the subcritical neutron amplifier on the basis of enriched uranium // *Problems of Atomic Science and Technology.* 2002, №6, p. 13-48 (in Russian).
5. J. Briesmeister. *MCNP General Monte Carlo Code N–Particle Transport Code Version 4C*, LA–13709–M.
6. Accelerator driven systems: Energy generation and transmutation of nuclear waste. IAEA, 1997.
7. H. Daniel, Yu.V. Petrov. Subcritical fission reactor driven by the low power accelerator // *Nucl. Instr. & Meth.* Section A. 1996, v. 373, p. 131-134.

ИССЛЕДОВАНИЕ ОДНОЗОННЫХ ПОДКРИТИЧЕСКИХ УСИЛИТЕЛЕЙ ПОТОКОВ НЕЙТРОНОВ НА ОСНОВЕ ОБОГАЩЕННОГО УРАНА

В.А. Бабенко, В.И. Гулик, Л.Л. Енковский, В.Н. Павлович, Е.А. Пупирина

Рассмотрены основные аспекты построения подкритических систем, способных усиливать нейтроны внешнего источника, касающиеся выбора источника нейтронов и оптимизации параметров подкритической системы. Представлены результаты расчетов коэффициентов усиления для однозонной сферической системы из обогащенного урана, однозонной сферической системы из раствора обогащенного урана в воде, а также для системы обогащенного урана, состоящей из сферической активной зоны и отражателя.

ДОСЛІДЖЕННЯ ОДНОЗОННИХ ПІДКРИТИЧНИХ ПІДСИЛЮВАЧІВ ПОТОКІВ НЕЙТРОНІВ НА ОСНОВІ ЗБАГАЧЕНОГО УРАНУ

В.О. Бабенко, В.І. Гулік, Л.Л. Єнковський, В.М. Павлович, О.О. Пупіріна

Розглянуто основні аспекти побудови підкритичних систем, здатних розмножувати нейтрони зовнішнього джерела, що стосуються вибору джерела нейтронів і оптимізації параметрів підкритичної системи. Представлено результати розрахунків коефіцієнтів посилення для однозонної сферичної системи зі збагаченого урану, однозонної сферичної системи з розчину збагаченого урану у воді, а також для системи збагаченого урану, що складається зі сферичної активної зони, і відбивача.