ACCELERATOR-DRIVEN SUB-CRITICAL RESEARCH FACILITY WITH LOW-ENRICHED FUEL IN LEAD MATRIX – NEUTRON FLUX CALCULATION

by

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The H5B is a concept of an accelerator-driven sub-critical research facility (ADSRF) being developed over the last couple of years at the Vinča Institute of Nuclear Sciences, Belgrade, Serbia. Using well-known computer codes, the MCNPX and MCNP, this paper deals with the results of a target study and neutron flux calculations in the sub-critical core. The neutron source is generated by an interaction of a proton or deuteron beam with the target placed inside the sub-critical core. The results of the total neutron flux density escaping the target and calculations of neutron yields for different target materials are also given here. Neutrons escaping the target volume with the group spectra (first step) are used to specify a neutron source for further numerical simulations of the neutron flux density in the sub-critical core (second step). The results of the calculations of the neutron effective multiplication factor k_{eff} and neutron generation time Λ for the ADSRF model have also been presented. Neutron spectra calculations for an ADSRF with an uranium target (highest values of the neutron yield) for the selected sub-critical core cells for both beams have also been presented in this paper.

Key words: cyclotron, accelerator-driven system, research reactor, neutron flux, fuel element

INTRODUCTION

A conceptual design of an accelerator-driven sub-critical research facility (ADSRF) was developed at the Vinča Institute of Nuclear Sciences in Belgrade over the past few years. The aim of this theoretical work is the study of modern reactor physics and development of technologies needed to design a small, fast or thermal, sub-critical low neutron flux reactor system driven by neutrons generated in a target by an accelerator beam [1]. The construction of nuclear power facilities is forbidden by law in Serbia [2]. Also, economic circumstances do not support the construction of an accelerator-driven sub-critical power system (ADS). Having in mind the current shortage of about 30% of electrical energy, in prospective, nuclear power plants may become a realistic option for producing electricity in the country. This conceptual design of a new, inherently safe sub-critical facility could become a focal point for the concentration and preservation of an ever smaller community of Serbian nuclear engineers.

The idea of a reactor with a neutron source generated by an accelerator beam originated in the late fifties of the 20th century. The modern concept of ADS has again come into the focus of the scientific community in subsequent decades of the 20th century when H. Takahashi in USA [3-4] and C. Rubbia in Switzerland [5-6] proposed their projects. A brief history of ADS was given in [7]. Large scale research ADS projects have been initiated world-wide in the last decade of the 20th century [8-9].

The concept of accelerator-driven systems combines a particle accelerator with a sub-critical core. The particle accelerator bombards a target which produces a neutron source. These neutrons can consequently be multiplied in the sub-critical core which surrounds the target (fig. 1.). The possibility to operate a reactor core at a neutron multiplication factor below one opens opportunities for new reactor concepts, including con-

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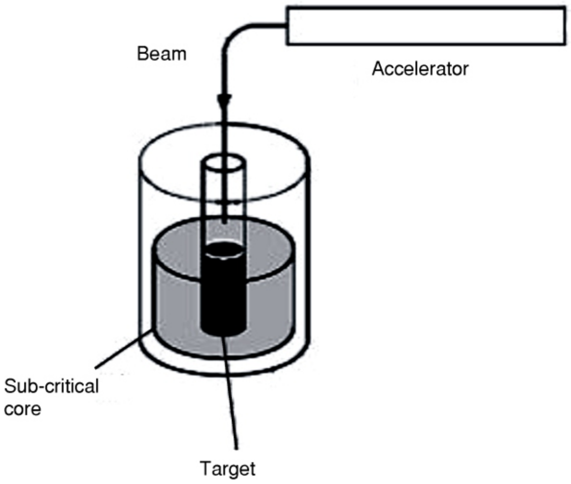

Figure 1. A sketch of an ADS

cepts which would otherwise be ruled out by an insufficient neutron economy. It appears that ADS have a great potential for radioactive waste transmutation and that they open the possibility of "burning" waste materials from existing reactors [8].

The results of the ADS studies carried out at the Vinča Institute from 1999 to 2006 can be found in refs. [1] and [10-16]. The H5B is a concept of an ADSRF developed at the Vinča Institute of Nuclear Sciences, Belgrade, Serbia. The H5B is supposed to use low-enriched (19.7% ^{235}U) uranium fuel of the TVR-S type of Russian origin, placed in a lead matrix. The neutron source is generated by an interaction of a proton or deuteron beam, to be extracted from the TESLA accelerator [17, 18] at the high energy channel H5B, with a target placed inside the sub-critical core. All basic parameters and specific data relevant to benchmark calculations of the H5B are given in [19].

This paper deals with the results of a target study and neutron flux calculations in the sub-critical core using well-known Monte Carlo computer codes. Simulations of proton and deuteron beam transport through the target so as to calculate the neutron yield and neutron emission spectra were carried out using the MCNPX2.4.0 code [20]. Neutrons escaping the target volume with group spectra (first step) were used to specify a neutron source for further numerical simulation of the neutron flux in the sub-critical core (second step). The MCNP5 code [21] is used for criticality calculations of the H5B ADSRF sub-critical core.

SIMULATION OF THE INTERACTION OF CHARGED PARTICLES WITH THE TARGET

In most cases, simulations of proton and deuteron transport through the target aimed at calculating the yield and neutron emission spectra were carried out using the MCNPX2.4.0 code and LA150 or ENDL92 data library [21]. Where these data libraries were nonapplicable, an analytical (Isabel) model of the MCNPX code for the interaction of charged particles with the target material was used.

With the purpose of neutron source simulations, a simplified beam model is proposed in which cylindrical symmetry and a continual time structure of the beam is assumed [19]. It has also been accepted that the radius of the beam circular transversal cross-section should be equal to the radius of the cylindrical source target. In this, extremely simplified model, it is assumed that the particles within the beam are uniformly distributed over the beam radius and that all particles move parallel to the direction of the beam. The characteristics of the assumed beam are described in tab. 1. The beam parameters are supposed to be used for a study of neutron production (yield and spectrum) of beam impact at the basis of the cylindrical target. One should note that the final results concerning the yield of the neutron source are normalized to N_{norm}, representing the number of ions in the beam hitting the target per a unit of time. This number depends on the ion beam current I_{beam} and the degree of ionisation n of a single ion in the beam. If the charge of each ion is defined by $Q = ne$, where n is an integer and e is the electron charge magnitude, then $N_{\mathrm{norm}} = I_{\mathrm{beam}}/ne = 6.242\ 10^{12}\ I_{\mathrm{beam}}/n$, where I_{beam} is given in μA and N_{norm} is given in s^{-1}.

Table 1. Beam specifications

Beam particle	E_0 [MeV]	$I_{\max}$ [μA]	N_{norm} [s^{-1}]
Proton (p)	73	5	$3.12\ 10^{13}$
Deuteron (d)	67	50	$3.12\ 10^{14}$

For the interaction of a charged particle beam with the target material, an idealized, cylindrical target of different, natural occurring materials in a vacuum (with no reflections of surrounding materials) is assumed. In each of the cases, the impact of the beam at the target basis is assumed to lie along the central axis of the cylindrical target, as shown in fig. 2. The impact area at the axis of the cylinder basis is assumed to be equal to the beam profile area (defined by the beam diameter). The model in question does not assume a window at the impact surface between the beam and the target.

Target dimensions are determined according to:

- available space inside the sub-critical core (maximum target diameter being 2.5 cm),
- a range of 73 MeV proton and 67 MeV deuteron in the target material (minimum target length), and
- basic cooling (thermal capacity) target requirements

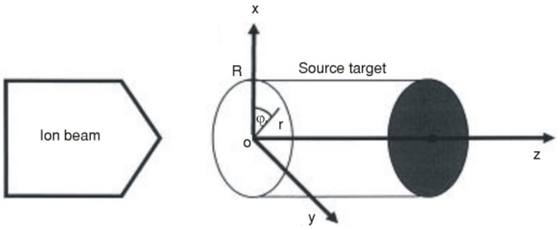

Figure 2. Sketch of an ion beam impact on the target

The ranges of charged particles with maximum beam energy in selected target materials, density of the target material, and specifications for a cylindrical target (material and dimensions) are given in [19].

Results for calculations by the MCNPX2.4.0 code were obtained for simulations of the interaction of beam particles with the target, sampling 1 000 000 initial particles, allowing a ±1% deviation from the basic beam energy, E_0. The neutron flux escaping the target surfaces was calculated to belong to the 62 energy group. Energy boundaries of the neutron group structures are given in [19].

The results of the calculations for the total neutron flux escaping the target and neutron yields for different target materials obtained by the MCNPX2.4.0 code are given in tabs. 2 and 3, respectively. Statistical errors for the neutron yield calculation results, *i. e.*, the standard deviations σ are shown here, too.

The highest values of the neutron flux $\Psi(E)$ were obtained for the uranium target, for both beams. The particle flux escaping the uranium target bombarded with deuteron and proton beams is given in figs. 3 and 4. Energy boundaries of the deuteron and proton group structures are the same as the neutron group structure. There is no deuteron flux escaping the target bombarded with a proton beam.

Neutron yields are calculated as the number of all neutrons leaving the target surfaces per an incident charged particle. The highest values of the neutron yield were obtained for the uranium target with a proton beam and for the beryllium target with a deuteron beam.

Table 2. Neutron flux obtained from different target materials

Target materijal	Proton beam		Deuteron beam	
	Neutron flux [cm^{-2}s^{-1}]	σ [%]	Neutron flux [cm^{-2}s^{-1}]	σ [%]
Lead	$1.325\ 10^{-3}$	0.52	$4.242\ 10^{-4}$	1.15
Uranium	$2.452\ 10^{-3}$	0.53	$7.125\ 10^{-4}$	0.88
Thorium	$2.092\ 10^{-3}$	0.54	$5.844\ 10^{-4}$	0.87
Bismuth	$1.412\ 10^{-3}$	0.51	$4.074\ 10^{-4}$	0.82
Lithium	$7.421\ 10^{-5}$	0.33	$4.402\ 10^{-5}$	0.47
Beryllium	$1.080\ 10^{-3}$	0.33	$7.948\ 10^{-4}$	0.47
Tungsten	$1.535\ 10^{-3}$	0.50	$4.967\ 10^{-4}$	0.80
Pb-Bi alloy	$1.415\ 10^{-3}$	0.51	$4.306\ 10^{-4}$	0.80

Table 3. Neutron yield obtained from different target materials

Target material	Neutron yield [%]	
	Proton beam	Deuteron beam
Lead	14.985	4.797
Uranium	27.728	8.058
Thorium	23.660	6.609
Bismuth	15.970	4.608
Lithium	13.429	7.966
Beryllium	12.210	8.989
Tungsten	17.357	5.617
Pb-Bi alloy	16.006	4.810

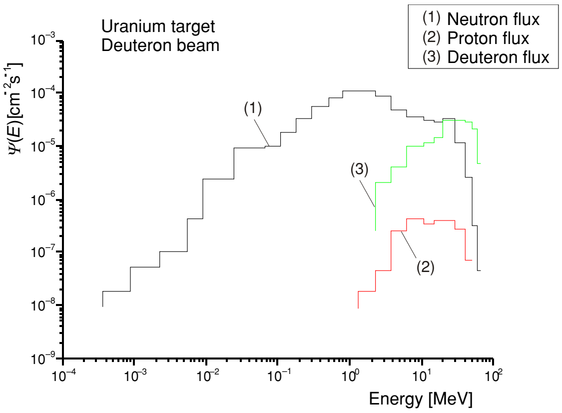

Figure 3. Particle flux escaping an uranium target – deuteron beam

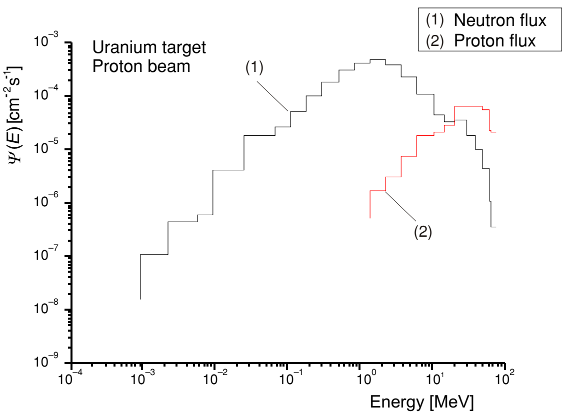

Figure 4. Particle flux escaping an uranium target – proton beam

The number of neutrons in an energy group per second and per squared centimetre Ψ_g, escaping the target's surfaces within the boundaries of a given energy group are given in figs. 5 and 6.

The graphs are normalized per one incident particle, so that the integral bellow $\Psi(E) - E$ graph (sum of products $\Psi_g E_g$) is normalized to one (eq. 1).

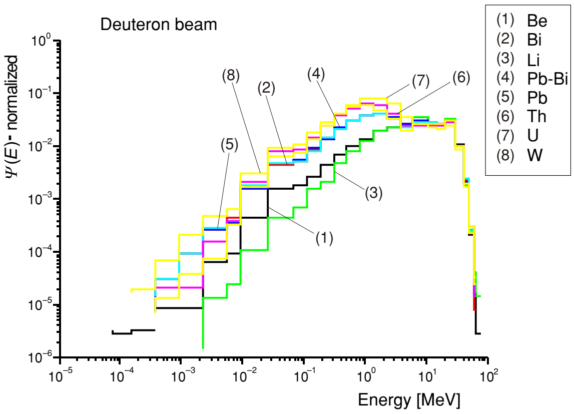

Figure 5. Neutron flux (normalized) for different target materials – deuteron beam

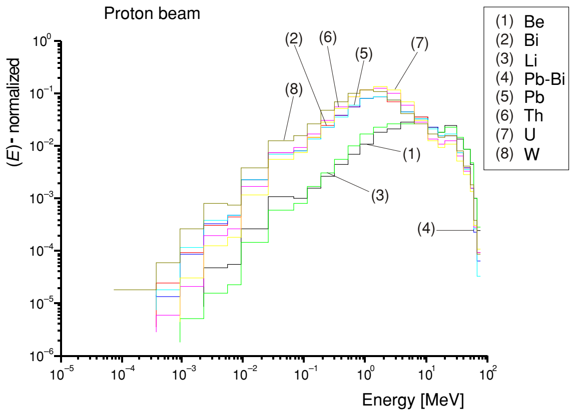

Figure 6. Neutron flux (normalized) for different target materials – proton beam

$$\int_{E_{\min}}^{E_{\max}} \Psi(E)\mathrm{d}E = \sum_{g=1}^{G_{\max}} \Psi_g(E)\,\Delta E_g = 1 \qquad (1)$$

Peaks of the escaping neutron spectra for both beams are in the energy range of 0.2 MeV to 4 MeV for all targets except beryllium and lithium. For these two targets, the peaks of the escaping neutron spectra are in the energy range of 1MeV to 10 MeV. There are no neutrons with energies bellow 1 keV, *i. e.*, there is no termalization of neutrons within the target material. This is a consequence of a simplification made in the simulation [15].

SIMULATION OF A NEUTRON FLUX IN THE SUB-CRITICAL CORE

The MCNP5 code is used for criticality calculations of the H5B ADSRF with the combination of the LA150 (neutron E_{max} = 150 MeV), used for major available nuclides, and ENDL92 (neutron E_{max} = 30 MeV) neutron cross-sections data libraries [21]. Only for a few nuclides (impurities in the ADS materials) ENDF-B/VI.8 (neutron E_{max} = 20 MeV) data are used.

A three-dimensional (3-D) model of the H5B ADSRF and a 3-D model of the TVR-S type fuel element for the MCNP code were developed and verified earlier [1]. The fuel element used for the H5B ADSRF design is the TVR-S type, produced at the Novosi- birsk Chemical Concentrate Plant, Novosibirsk, Russian Federation. It is a tubular-type fuel element with cladding made of the aluminum alloy SAV-1. The fuel layer is designed as uranium dioxide dispersed in an aluminum alloy matrix. This design supposes that 19.7% ^{235}U enriched LEU fuel elements are available. Seven TVR-S fuel elements are placed into one fuel assembly (FA) tube filled with a primary moderator. Demineralised water was used as a primary moderator. The sub-critical core was assembled inside the cylindrical tank made of stainless steel (SS). The inner and outer diameters of the tanks are 1000 mm and 1050 mm, respectively. The tank wall has the same thickness as the bottom cylindrical plate of the tank: 25 mm. For the purposes of the model, the tank height is assumed to match exactly the total height of the core and both axial reflectors, *i. e.*, to be 1037 mm. The core section was assembled using 109 FA arranged within a regular 11 11 matrix in the central part of the tank. The pitch of this square lattice is 50 mm. The central FA is coaxial with the tank axis. The total number of LEU TVR-S fuel elements used for the core design is 759. Each of the 109 FA has 7 fuel elements, as described, except the central one. The central FA has only three fuel elements placed at the bottom of the tube, covered by demineralised water. This FA tube has a hole (of a diameter of 30 mm) at the top plug for the penetration of the beam guide tube made of SS. A target is placed at the bottom of the beam guide tube, in high vacuum. The core is moderated and reflected by lead that, for the purposes of the model, matches exactly the inner wall of the core tank. Detailed core description and material specifications are given in [19].

Neutrons escaping the target volume with group spectra obtained in the MCNPX2.4.0 code (first step) are used to specify the neutron source distribution for further numerical simulations of the neutron flux in the sub-critical core (second step). In this (second) step of the calculation by the MCNP5 code, 2000 neutron active cycles have been run with 2500 neutrons per cycle, after 200 initial ones. The neutron spectra in various cells of the ADSRF lattice were calculated in 58 energy groups. Energy boundaries of the neutron group structures are given in [19]. The results of the calculations of the neutron effective multiplication factor k_{eff} and neutron generation time Λ for the H5B ADSRF model are given in tabs. 4 and 5, including the uncertainty equal to the statistical standard error σ in calculations with a coverage factor equal to 1.

The calculated neutron effective multiplication factor k_{eff} is less than 0.98 for the ADSRF, for all targets and both beams, so the prerequisite for the inherent safety of the sub-critical reactor has been kept. All

Table 4. Neutron effective multiplication factor k_{eff}

Target	k_{eff} σ_k			
	Proton beam		Deuteron beam	
Lead	0.97444	0.00032	0.97440	0.00033
Uranium	0.97358	0.00032	0.97374	0.00032
Thorium	0.97384	0.00033	0.97399	0.00034
Bismuth	0.97432	0.00033	0.97431	0.00033
Lithium	0.96849	0.00034	0.96910	0.00033
Beryllium	0.97450	0.00033	0.97447	0.00034
Tungsten	0.97306	0.00033	0.97309	0.00033
Pb-Bi alloy	0.97440	0.00033	0.97450	0.00033

Table 5. Prompt neutron removal life-time

Target	Λ σ_Λ [μs]			
	Proton beam		Deuteron beam	
Lead	77.183	0.045	77.306	0.044
Uranium	77.180	0.044	77.226	0.047
Thorium	77.130	0.045	77.187	0.045
Bismuth	77.241	0.045	77.222	0.045
Lithium	76.847	0.045	76.858	0.046
Beryllium	77.305	0.045	77.202	0.045
Tungsten	77.065	0.046	77.149	0.046

the values of k_{eff} are close to 0.97, meaning that the conditions for neutron multiplication are good.

In the H5B ADSRF, neutron spectra with the uranium target (highest values for the neutron yield escaping from the target), for the following cells, for both charged particle beams (deuteron and proton), are calculated as follows:

– bellow the target,
– beside the target in the radial direction,
– at the core edge to the reflector, at the core height of the target, and
– at the reflector cell at the tank edge, at the core height of the target.

Neutron spectra in the H5B ADSRF with an uranium target, for the above mentioned cells, are given in figs. 7 and 8. All the curves of the core cells have almost the same shape. Neutron spectra for the reflector cell at the tank edge in the highest energy range (more than 1 MeV) are slightly different from those from the core cells in the same energy range.

The total neutron flux escaping the cells of the H5B ADSRF with an uranium target is given in tab. 6. The uncertainty equal to the standard statistical error σ for calculations with a coverage factor equal to 1 is shown, too. It is obvious that the highest values of the neutron flux are obtained in cells closest to the target.

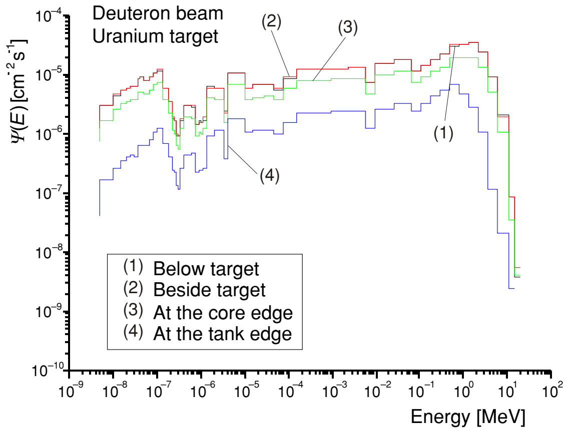

Figure 7. Neutron flux in H5B ADSRF with an uranium target and a deuteron beam

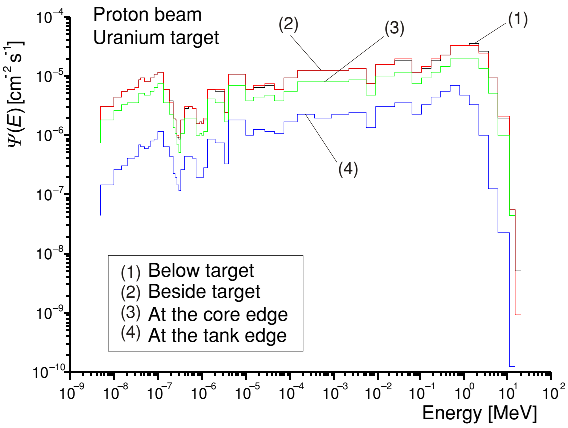

Figure 8. Neutron flux (normalized) in H5B ADSRF with an uranium target and a proton beam

Table 6. Total neutron flux in cells for H5B ADSRF with an uranium target

Cell	Proton beam		Deuteron beam	
	Neutron flux [cm^{-2}s^{-1}]	σ [%]	Neutron flux [cm^{-2} s^{-1}]	σ [%]
Below the target	4.86754 10^{-4}	0.36	4.87829 10^{-4}	0.36
Beside the target in a radial direction	4.91460 10^{-4}	0.36	4.94015 10^{-4}	0.36
Core edge to the reflector, core height of the target	3.00569 10^{-4}	0.48	3.00500 10^{-4}	0.47
Reflector cell at the tank edge, core height of the target	7.01147 10^{-5}	1.02	7.06248 10^{-5}	1.03

CONCLUSION

Simulations of proton and deuteron beam transport through the target with the aim of calculating neutron yield and neutron emission spectra were carried out using the MCNPX Monte Carlo code. The highest values for the neutron yield were obtained for the uranium target with a proton beam and a beryllium target with a deuteron beam. The peaks of the escaping neutron spectra for both beams are in the energy range of 0.2 MeV to 4 MeV for all targets, except those made of beryllium and lithium, the said targets being in the range of 1 MeV to 10 MeV.

The MCNP5 Monte Carlo code is used for criticality calculations of the sub-critical core of the H5B ADSRF. The total neutron flux in some of the represented cells of the H5B ADSRF core with an uranium target is also presented here. As expected, the highest values of the neutron flux are obtained in cells closest to the target. The calculated neutron effective multiplication factor k_{eff} is around 0.97 for H5B ADSRF, for all studied targets and both charge particle beams. Neutron spectra in the H5B ADSRF with an uranium target for the selected cells are given, too. All neutron spectra in core cells exhibit an almost identical shape. Neutron spectra in the reflector cell at the tank edge are slightly different from those in the core cells in the highest energy range.

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ПОТКРИТИЧНО ИСТРАЖИВАЧКО ПОСТРОЈЕЊЕ СА НИСКООБОГАЋЕНИМ ГОРИВОМ У ОЛОВНОЈ МАТРИЦИ ПОКРЕТАНО ПОМОЋУ АКЦЕЛЕРАТОРА – ПРОРАЧУН НЕУТРОНСКОГ ФЛУКСА

Ха5Бе (H5B) је концепт поткритичног истраживачког постројења покретаног помоћу акцелератора који је развијен у последњих неколико година у Институту за нуклеарне науке „Винча" у Београду. У раду су приказани резултати прорачуна густине неутронског флукса добијеног у мети и поткритичном језгру помоћу добро познатих Монте Карло рачунарских програма (MCNPX и MCNP). Неутронски извор се генерише интеракцијом протона или деутерона из акцелераторског снопа са метом постављеном у поткритично језгро. Приказани су резултати прорачуна густине неутронског флукса који излази из мета као и принос неутрона за мете од различитог материјала. Групни спектар неутрона који напуштају мету (први корак у прорачуну) коришћен је за дефиницију извора у даљој нумеричкој симулацији густине неутронског флукса у поткритичном језгру (други корак у прорачуну). Приказани су резултати прорачуна ефективног фактора умножавања k_{eff} и време стварања неутрона Λ. Прорачун густине неутронског флукса у поткритичном језгру урађен је за постројење са метом од уранијума (мета са највећим вредностима густине излазног неутронског флукса) и за обе врсте акцелераторског снопа (протони и деутерони).

Кључне речи: циклотрон, постројење покретано акцелератором, истраживачки реактор, густина неутронског флукса, горивни елемент