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# NEUTRONIC LIMITS IN VARIOUS TARGET MEDIUMS DRIVEN BY A PROTON BEAM OF 1 GeV ENERGY

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## ABSTRACT

The concept of accelerator-driven system (ADS) combines a particle accelerator with a sub-critical core. The basic process in an ADS is nuclear transmutation, and in general, an ADS consists of three parts: (1) accelerator, (2) spallation neutron target (SNT) and (3) sub-critical core (often called a blanket) which surrounds the SNT. This study presents the neutronic limits in various infinite target mediums driven by a proton beam of 1 GeV energy. Lead-bismuth eutectic, mercury, tungsten, uranium, thorium, chromium, cupper and beryllium are considered as the target material. Furthermore, the calculation is performed for also dual mixture of lead-bismuth eutectic and uranium. In order to be able to simulate the infinite target medium by eliminating the spatial dependence, a spherical target is considered, and its radius is increased gradually up to adequate radius ensuring the infinite target medium. In this way, the radius value ensuring the maximum neutron leakage out of the target would be determined. Numerical calculations were performed with the high-energy Monte Carlo code MCNPX in coupled neutron and proton mode using the LA150 library.

**Keywords:** Infinite medium calculations; Spallation neutron target; Spallation neutrons; Proton accelerator

## I. INTRODUCTION

Conventional power reactors generally do not require external neutron sources for normal operation. These reactors are based on the self-multiplication of neutrons in a critical state. In a critical reactor the fission reactions alone are able to maintain a steady-state. In contrast, the accelerator-driven system (ADS) is a subcritical reactor driven by an external neutron source. The external source is maintained by a spallation neutron target (SNT) driven by a high power (usually >500 MeV) proton accelerator. The protons impinge on a SNT, generating a large number of neutrons via spallation. The spallation neutrons (SNs) leak out from the target, after different kinds of interactions with the target nuclei, and are subsequently multiplied in the surrounding sub-critical blanket. Thus, the neutron economy is enhanced by further multiplying the spallation neutrons in a sub-critical medium. The SNs can be used to transmute the highly-radiotoxic nuclei which are present in nuclear waste into stable or very short lived isotopes that can be disposed off safely. The neutron yield per incident intermediate proton is the most interesting data for the practical application in the ADS study due to the fact that the number of SNs per incident proton depends on the beam energy and on the mass of the target nuclei. Therefore, optimizing the size of the target and thereby maximizing the neutron leakage from the target can have an important impact on the overall design of an ADS. A great number of works on the ADSs and on their neutronics have studied by many researchers. Most of them were concerned with specific design concepts. Furthermore, the SN production in various target mediums with specific dimensions has been analyzed for several proton beam energies [1-15].

Infinite medium calculations, performed by varying material composition and size of the target, would eliminate the spatial dependence and would supply general data as guidelines for design studies by indicating the upper limits of the integral neutronic quantities. Infinite medium calculations for various nuclear fuels (such as uranium and thorium) and materials (such as lithium, beryllium and lead) exposed to (D,T) fusion neutrons were studied [16-18].

In this paper, we investigate the neutronic limits for various infinite target mediums driven by energetic protons. These neutronic limits would light the way for the size of the SNT in the ADSs.

## II. THE SPALLATION NEUTRON TARGET (SNT)

The SNT is the physical barrier between the accelerator and the core, and must withstand severe damage due to high-energy particles and thermal load. A material with high neutron yield, good physical and chemical properties and thermal-hydraulic performance must be chosen. Two main options for the SNT material are being considered; solid or liquid metal. While all current spallation sources operate with a solid metal target, the heavy liquid metal (HLM) choice appears to be the only realistic one for a large scale ADS, due to the extremely high power densities. The main advantages of liquid metals are the superior heat removal capabilities and the significant reduction of the radiation damage to the target. Nowadays, among the HLM, Pb or lead (Pb)-bismuth (Bi) eutectic (LBE, 44.5% Pb, 55.5% Bi) are the best candidates for ADS, due to the chemical and thermodynamical features: chemical inertia, high boiling temperature, relatively low melting temperature, heat conductivity etc. Furthermore, since liquid metals are known to have good heat transfer rates, liquid LBE might also be considered for use as a coolant. Mercury (Hg) has also been considered as a spallation target material because of its low melting point. Tungsten (W) being a producer of neutrons can be a good candidate for the solid target material because of its properties of corrosive resistant, high thermal conductivity and high melting point. There is extensive experience in using it as a neutron source. Many uranium (depleted or enriched) targets have so far been used in various spallation neutron facilities of small and medium proton beam powers due to their higher neutron yield per proton compared to the other non-actinide heavy metal targets.

The design of the SNT should be based on the optimization of neutronic efficiency. As the diameter/length of the target increases, more neutrons are produced because high energy particles have more chances of the neutron production reaction before they escape from the target. In the HLM targets, the protons do not penetrate deeply and majority of neutrons are produced in the first about 20 cm of the target. The spallation reactions emit a few tens of neutrons per incident proton. These neutrons are introduced into the sub-critical core to induce further nuclear reactions. Number of produced neutrons (PN) can be determined by summing number of captured neutrons (CN) and number of leaking neutrons (LN). Therefore, optimization for the neutron leakage is equivalent to optimization for the neutron production and the neutron capture. In other words, the target section of an ADS should be configured in a most suitable shape and size that realize the maximum neutron leakage.

LBE, Hg, W, uranium (U; 99.3% $^{238}$U fertile and 0.7% $^{235}$U fissile), and thorium (Th) are considered as the SNT material, (first group target materials), because of their high atomic number and their favorable spallation-neutron production characteristics. Furthermore, chromium (Cr), cupper (Cu) and beryllium (Be), (second group SNT materials), which have low SN production characteristics, are also analyzed from the neutron leakage point of view as the pure target material. In addition to these analyses, the calculation is performed for also dual mixture of LBE and U, (mixed target). The densities and isotope compositions of all considered target materials are given in Table 1.

## III. CALCULATIONAL METHOD

The neutronic calculations have been performed per the incident proton (1000 MeV) with the high-energy Monte Carlo code MCNPX [19] in coupled neutron and proton mode using the LA150 library [20]. This library consists of evaluated reaction cross sections and emission spectra up to 150 MeV for incident neutrons and protons, for over 40 target isotopes important in spallation targets, structural materials, and shielding. The intranuclear cascade of spallation reactions is simulated using Bertini INC model [21].

In order to be able to simulate the infinite target medium, in which the LN is zero, by eliminating the spatial dependence, a spherical target is considered. A spherical target is hard to be implemented in an accelerator-driven system. However, the main aim of this study is to light the way for actual ADS design studies by presenting comprehensive general neutronic data limits for various composition and sizes of the SNT. In the case of the infinite target medium, all produced neutrons are captured by the target material. It is assumed that an isotropic point source of 1000 MeV incident proton is positioned at the center of the target. This incident proton energy is approximately the level where increasing the energy does no longer increase the effective neutron yield per energy unit. The target radius (R) is increased gradually up to adequate radius ensuring the infinite target medium. This radius ($R_\infty$) is different for each target material.

Table 1. Densities and isotopic fractions of the considered target materials

| Target material | Density [g/cm$^3$] | Isotope | Isotopic Fractions [%] |
|---|---|---|---|
| Beryllium | 1.850 | $^{9}$Be | 100 |
| Bismuth | 9.800 | $^{209}$Bi | 100 |
| Chromium | 7.200 | $^{50}$Cr | 4.174 |
| | | $^{52}$Cr | 83.700 |
| | | $^{53}$Cr | 9.673 |
| | | $^{54}$Cr | 2.453 |
| Copper | 8.920 | $^{63}$Cu | 68.499 |
| | | $^{65}$Cu | 31.501 |
| Lead* | 11.344 | $^{206}$Pb | 24.000 |
| | | $^{207}$Pb | 22.900 |
| | | $^{208}$Pb | 53.100 |
| Mercury | 13.546 | $^{196}$Hg | 0.146 |
| | | $^{198}$Hg | 9.869 |
| | | $^{199}$Hg | 16.763 |
| | | $^{200}$Hg | 23.028 |
| | | $^{201}$Hg | 13.225 |
| | | $^{202}$Hg | 30.004 |
| | | $^{204}$Hg | 6.965 |
| Thorium | 11.700 | $^{232}$Th | 100 |
| Tungsten* | 19.350 | $^{182}$W | 26.068 |
| | | $^{183}$W | 14.250 |
| | | $^{184}$W | 30.716 |
| | | $^{186}$W | 28.966 |
| Uranium | 19.050 | $^{235}$U | 0.700 |
| | | $^{238}$U | 99.300 |

*Due to the fact that there are no data for $^{204}$Pb and $^{180}$W the abundances of which are 1.378 and 0.117, these fractions are merged into the amount of other isotopes of Pb and W, respectively.

## IV. NUMERICAL RESULTS

The maximum neutron yield and spectrum of leaking neutrons from the target surfaces have an important impact on the ADS design. The variations of the fractions of leaking neutrons below 20 MeV in the total neutron leakage for the various target materials (first and second group target materials) versus different target radii are plotted in Figure 1. The fraction profiles increase quasi-logarithmically with the increase of the target radius from 10 cm to a certain value. While the ratio of the leaking neutrons below 20 MeV in the first group target materials is in the range of 92 to 99%, this ratio for the second group target materials is in the range of 75 to 97%.

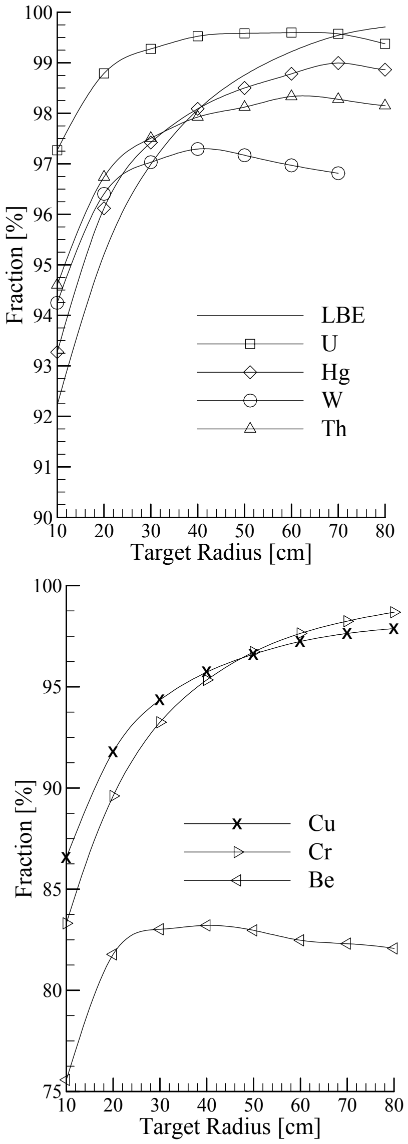

Figure 1. Fraction of leaking neutrons below 20 MeV in the total neutron leakage for different target radii

Figure 2 shows the CN and LN profiles in the first group target materials versus the different target radii. The PN can be easy obtained from these figures by summing the CN and the LN. As mentioned in section III, in the infinite target medium, the PN is equal to the CN. LN values increase to a certain value, and then decreases exponentially to zero. The radius values ensuring the maximum neutron leakage are determined from these inflection points. Both of the target radii ensuring the infinite target medium and the maximum neutron leakage ($R_\infty$ and $R_{maxL}$) are different for the each target materials due to the fact that each one of them exhibit different neutronic behavior. In the first group target materials except for LBE, the $R_\infty$s vary in the range of 80-120 cm. These values are quite small with respect to the LBE target in such a way that the in the LBE target $R_\infty$ is equal to 400 cm. Although the number of produced neutrons is the highest in the U target, the majority of these neutrons are captured. The maximum neutron leakage quantities are approximately 30, 29, 19, 18 and 18 n/p in the LBE, U, Hg, W and Th targets, respectively, when the target radius is equal to the value of their $R_{maxL}$s, respectively.

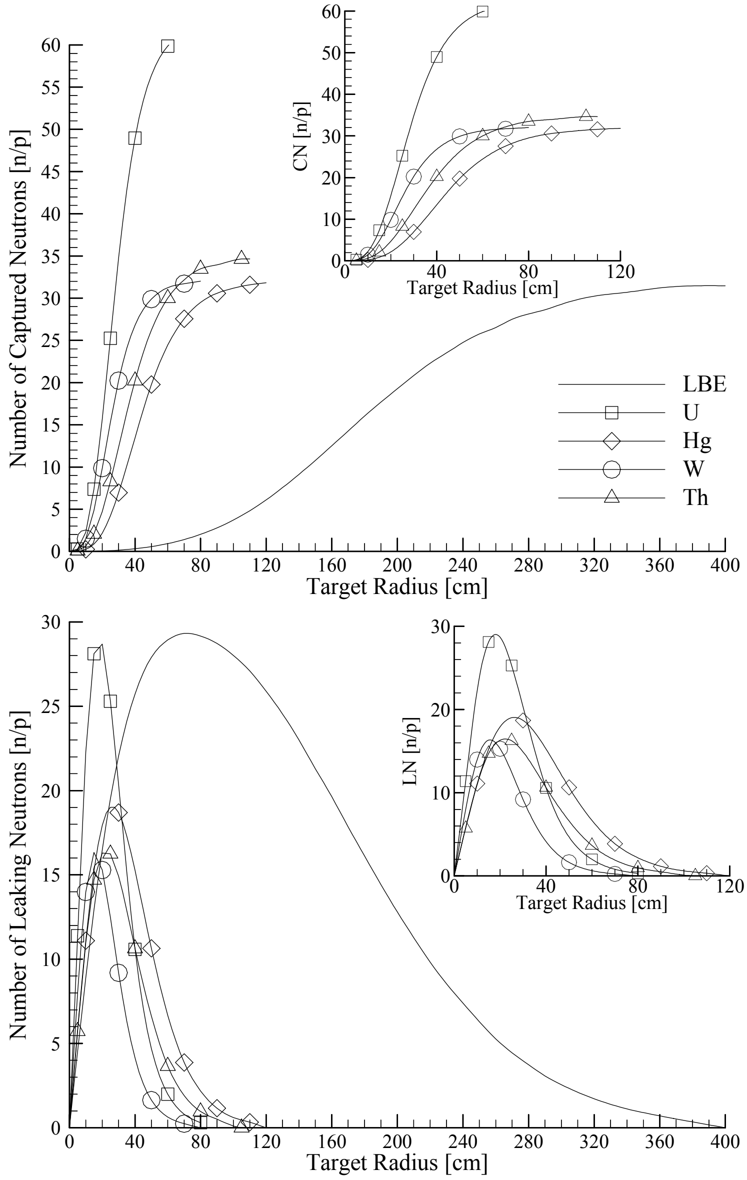

Figure 2. Numbers of captured and leaking neutrons in the considered targets for different target radii

Figure 3 illustrates the CN and LN profiles in the second group target materials versus the different target radii. The target radii ensuring the zero and maximum neutron leakages are (220 and 48), (160 and 31) and (180 and 34) in the Cr, Cu and Be targets, respectively. As mentioned above that the number of SNs per incident proton depends on the mass of the target nuclei. As is apparent from this figure, the maximum neutron leakage quantities of second group target materials are an extremely low with respect to first group target materials. They reach barely to 9, 8 and 4 n/p in the Cr, Cu and Be targets, respectively, when the target radius is equal to the value of their $R_{maxL}$s.

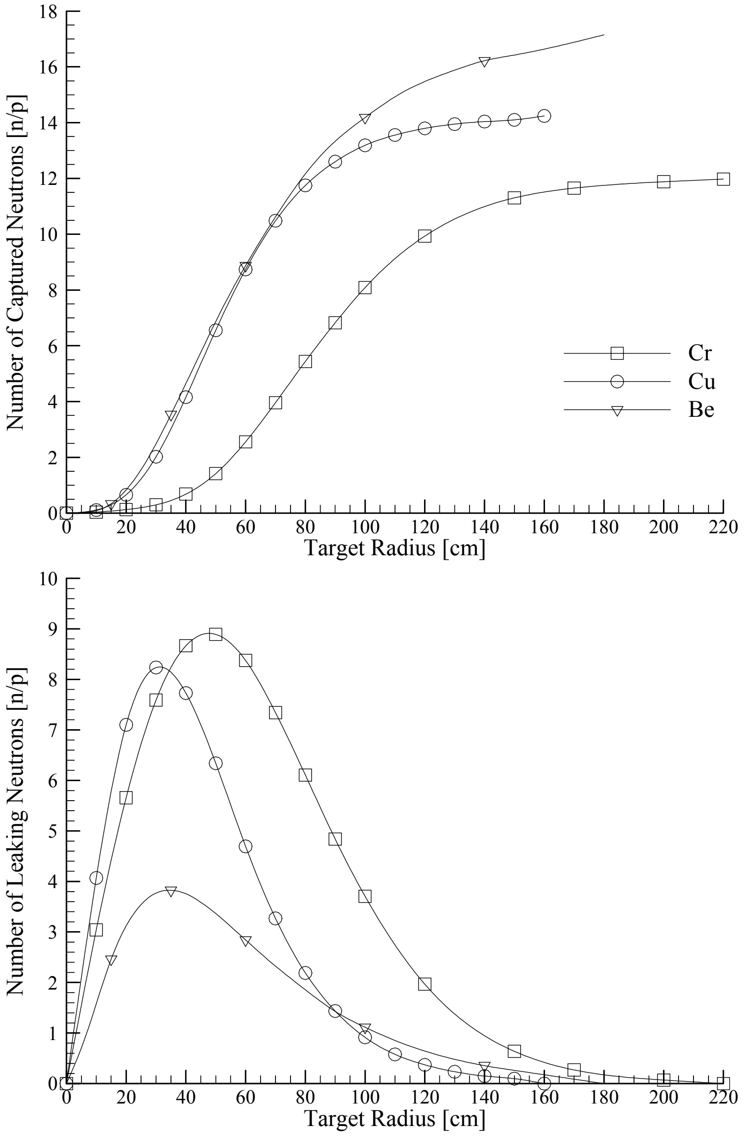

Figure 3. Numbers of captured and leaking neutrons in the Cr, Cu and Be targets for different target radii

The CN and LN profiles in the LBE target mixed with U at the various volume fractions (0, 25, 50 and 100%) are plotted versus the different target radii in Figure 4. As the VF of U in the mixture targets increases from 0 to 100%, both of the target radii ensuring the infinite target medium and the maximum neutron leakage ($R_\infty$ and $R_{maxL}$) decrease significantly. $R_\infty$ decreases from 400 to 80 cm, and $R_{maxL}$ decreases from 72 to 18 cm, and the $LN_{max}$ does not almost change in the mixture with U, (29 n/p). The CN is 2 and 12 n/p in the pure LBE and U targets in which the target radius is equal to the value of their $R_{maxL}$s, respectively. These results bring out that the thickness of a LBE target would be reduced at the considerable ratios when it is mixed with the U target even at the low VFs in such a way that at the VF = 25%. While the target thickness becomes smaller about 50% in the LBE targets mixed with U, the $LN_{max}$ decreases only 6%, respectively. The target is a neutron source, and it is desirable that all neutrons produced in the target leave it and enter to the sub-critical zone. This condition would be fulfilled with the target having small dimensions. The LBE target will also serve as coolant in the mixtures with the solid materials.

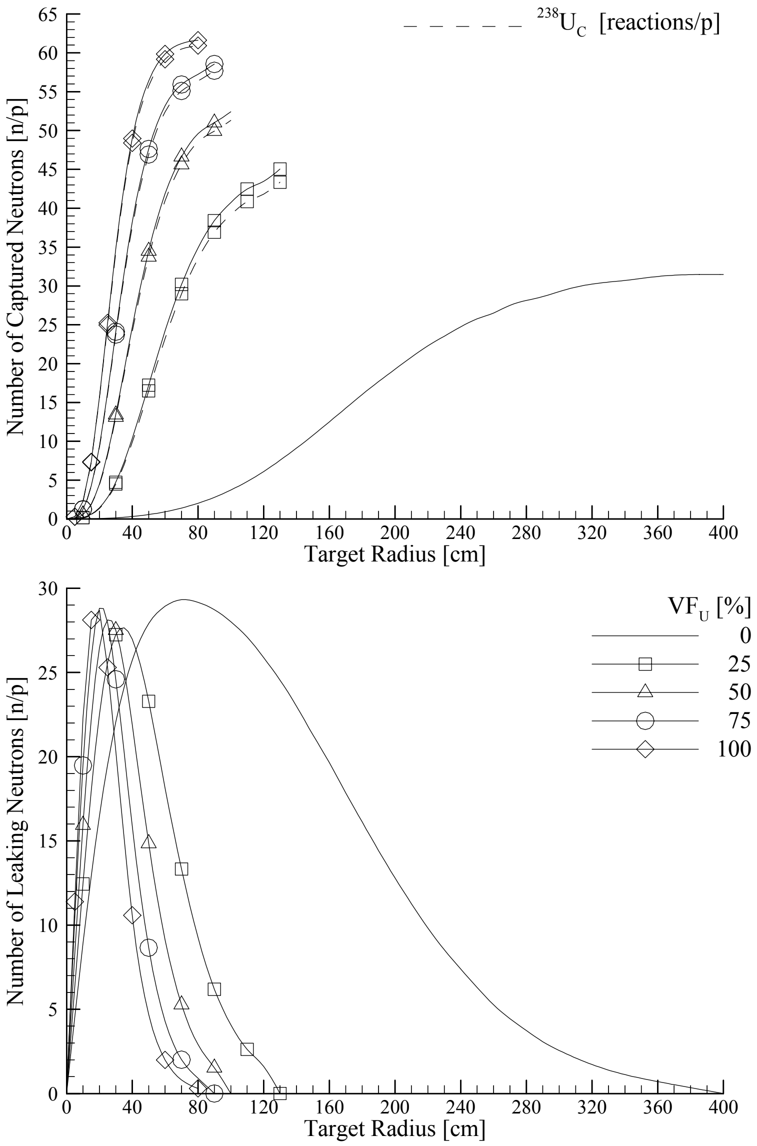

Figure 4. Numbers of captured and leaking neutrons in the LBE-U target at various volume fractions for different target radii

A neutron capture in a fertile nuclide, followed by two successive β emissions, leads to the production of a fissile nuclide. In the target containing the fertile materials (such as $^{238}U$), in addition to the SN production, the fissile fuels ($^{239}Pu$) are bred from $^{238}U$ via the fertile to fissile conversion reactions. These fertile targets can be further fissioned by the SNs which in turn produce additional neutrons. In the mixture with U, a great ratio of the CN belongs to the capture of $^{238}U$ (see Figure 4). This exhibits that in addition to the neutron production, it is possible to breed fissile $^{239}Pu$ at a considerable amount in the target by means of the capture reactions of $^{238}U$.

In the infinite target medium case, all neutrons produced by the nuclear interactions in the target are consumed again within the target by means of capture reaction. The variations of the capture and fission reactions per the incident source proton in the infinite target mediums containing the mixture of LBE and U with the mixture fraction are presented in Figure 5. In the case of the pure U, the fissile $^{239}Pu$ breeding and fission reactions reach to 62 and 15 reactions/p, respectively. These values are quite high with respect to in the same infinite target mediums driven with the catalyzed DD and DT neutrons (see Figure 6).

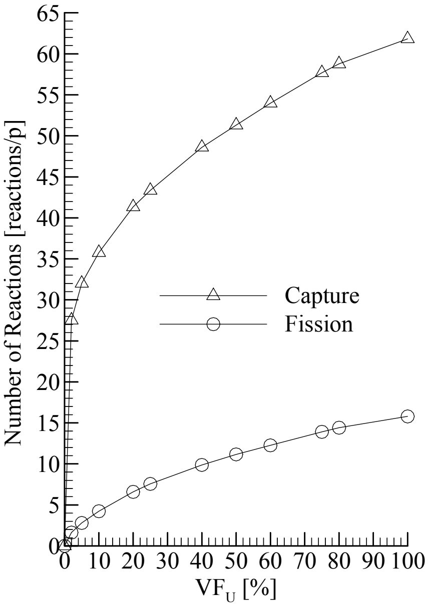

Figure 5. Variations of the capture and fission reactions in the infinite target mediums containing the mixtures of U and LBE with the mixture fraction

## V. CONCLUSIONS

The purpose of this paper is to investigate the neutronic limits for various infinite target mediums driven by energetic protons to light the way for the determinations of composition and size of the SNTs. The mixing of the LBE with the U target material lowers significantly the target radius ensuring the maximum neutron leakage. More the SNs are produced by using uranium target with the smaller target sizes with respect to the pure LBE and other targets. In addition to the neutron production, it would breed the fissile $^{239}$Pu in the considerable amount. These results obtained with the infinite medium approach would guide for actual ADS designs.

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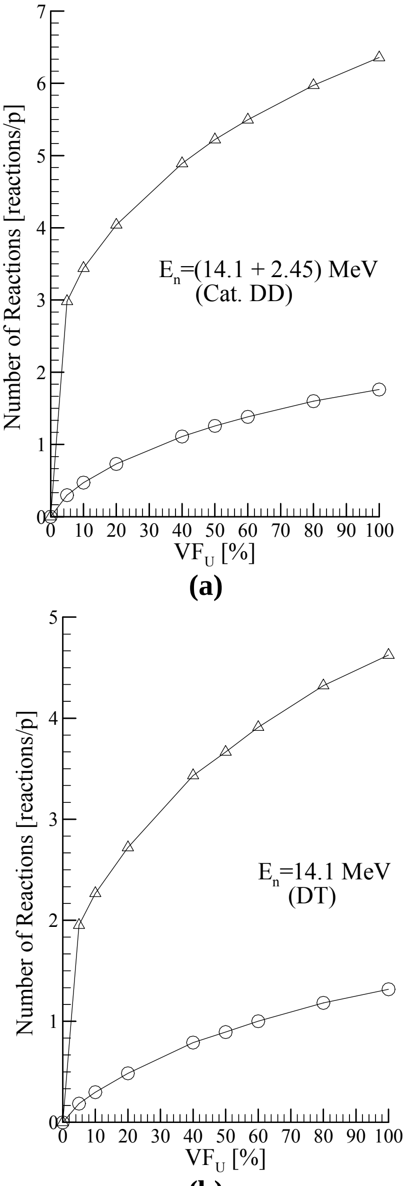

**(a)**

**(b)**

Figure 6. Variations of the capture and fission reactions per the incident source nucleon, (a) catalyzed DD neutrons (14.1 and 2.45 MeV), and (b) DT neutron (14.1 MeV) in the infinite target medium containing the mixture of LBE and U with the mixture fraction

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## Nomenclature

*Abbreviation*

| | |
|---|---|
| ADS | Accelerator-Driven Systems |
| CN | Number of captured neutrons [n/p] |
| HLM | Heavy liquid metal |
| LN | Number of leaking neutrons [n/p] |
| PN | Number of produced neutrons [n/p] |
| SNS | Spallation neutron source |
| SN | Spallation neutron |
| SNT | Spallation neutron target |

*Subscript*

| | |
|---|---|
| max | Maximum |
| maxL | Target radius ensuring maximum neutron leakage |
| ∞ | Target radius ensuring infinite target medium (zero neutron leakage) |