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Ability to Make Accelerator-Driven Sub-Critical Reactor System (ADS) Without A Separate Spallation Target for (p,n) Reaction

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Abstract
We introduce the idea of using liquid lead which makes not only a coolant but also a spallation target for (p,n) reaction in Accelerator-driven sub-critical reactor system (ADS). So the target will not need to be replaced during nuclear reactor operation. The entire volume of liquid lead on the path of the incident proton beam in the ADS will be the spallation target; therefore, the number of neutrons generated is not less than those generated by the conventional target method. We provide preliminary calculations illustrating the above ideas. We present two models to calculate the number of neutrons and the neutron multiplicity using database of JENDL/HE library [11]. The number of neutrons and the neutron multiplicity are calculated with the proton beam bombardment on the liquid lead coolant at beam energies of 200 MeV, 250 MeV, 350 MeV, 500 MeV, 600 MeV, 700 MeV, 800 MeV, 1000 MeV and 1500 MeV. The calculated results are compared with the available data [8].

1. Introduction

In the 80s and 90s, the idea of Accelerator-driven sub-critical reactor system (ADS) was mentioned by K. Furukawa et al. [1], C. D. Bowman et al. [2] and C. Rubbia et al. [3], and so far very many people have concerned and researched ADS [4 - 10] because it could have the advantages which outweigh traditional nuclear reactor such as higher safety, the possibility of using various fuels, incinerating radioactive waste and producing energy. However ADS fabrication and operation have a lot of difficulties. One of the difficulties is generating additional neutron, the fuel in the reactor is subcritical so we have to use the proton beam from the accelerator interacts with the target to produce (p,n) nuclear reaction and neutrons generated in this reaction are called additional neutrons. As a result, the subcritical system in the reactor becomes critical. All operational processes and controls the reactor depend on the number of additional neutrons. Thus, to operate the reactor, a spallation target must be used. Then the proton beam interacts with the target to generate (p,n) nuclear reaction. Every target has a certain life-span, after a period of operation the target must be carried out to change, this is a very difficult task which takes long time and requires shutting down the reactor. In this article, we present the idea of directly using the lead coolant in the reactor as the spallation target, the proton beam will interact directly onto the lead. There will be great advantages in this way:

1) There needn't be the spallation target, instead, we directly use lead not only as the coolant but also the spallation target which interacts with proton beam from the accelerator. So, we will not change the target, manufacture the target and the reactor will not be shut down during the process of operation.

2) Proton beam will interacts directly with lead (Fig. 1). The entire lead which is located on the diameter of the reactor will become the spallation target, the length of the target increases and thus the number of neutrons produced also increases.

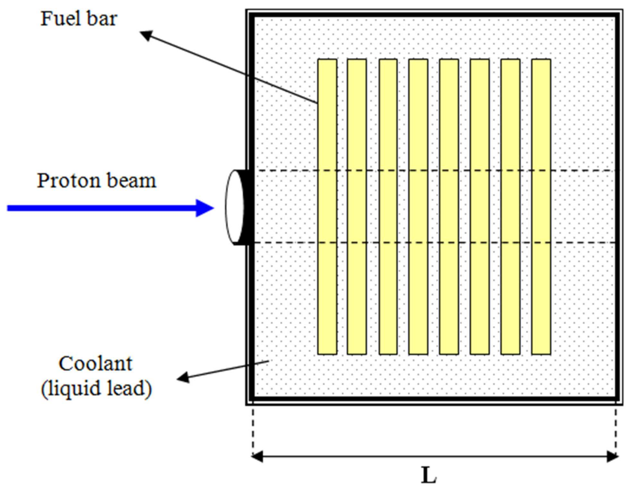


Fig. 1. *An ADS model uses liquid lead which makes not only a coolant but also a spallation target*

In this paper, we calculate the number of neutrons produced by using data from JENDL/HE nuclear library [11]. We assume that (p,n) reaction in the lead is homogeneous. This calculation presented in 2.1 is only approximate. In fact**,** when protons pass through lead, proton energy will decrease and protons will be scattered in many directions, so the number of protons also loses but in the calculation we take into account the number of protons which is constant during the process of interaction, the energy is not lost in the process of interaction. To overcome this problem we have used the screening effect model [6]: to calculate the number of neutrons produced per layer and the number of neutrons obtained will be the total number of neutrons produced in all layers. This calculation is presented in 2.2.

We assumed as follow:

- The initial energy of the proton: 200 MeV, 250 MeV, 350 MeV, 500 MeV, 600 MeV, 700 MeV, 800 MeV, 1000 MeV, 1500 MeV.
- Proton beam diameter: D = 10.2 cm
- Current intensity of accelerator: I ~ 10 mA

Initially, we assumed the reactor is a homogeneous block containing lead. That means the effects of other materials in the reactor such as fuel, structural material, moderator, absorber....are not taken into account. These effects will be added later in the coming research. Proton beam is parallel beam with a cylindrical form, interact only within the proton beam diameter. In the below calculations, to easily compare with results of international work, we consider the length of the reactor diameter L is 60 cm, after that we increase the length L = 120 cm, 180 cm, 240 cm, 300 cm.

2. Formula and Calculation Model

We have calculated the number of neutrons produced from (p,n) nuclear reaction based on (p,n) reaction cross section formula [12]:

$$\sigma_i(\mu, E, E') = \sigma(E)\, y_i(E)\, f_i(\mu, E, E') \qquad (1)$$

where:

- i denotes one particular product
- E is the incident energy
- E' is the energy of the product emitted with cosine μ
- $\sigma(E)$ is the interaction cross section
- y_i is the product yield or multiplicity
- f_i is the normalized distribution with units (eV .unit-cosine)$^{-1}$ where

$$\int dE' \int d\mu f_i(\mu, E, E') \qquad (2)$$

2.1. Homogeneous Model

To calculate the number of neutrons produced from (p,n) reaction, initially we suppose lead is a homogeneous block, proton beam does not change the intensity as well as energy throughout the length of interaction, this computational model is called a homogeneous model (Fig. 2).

With the homogeneous model we calculate the number of neutrons produced at 9 incident energies of proton from 200 MeV to 1500 MeV (Table 1).

Table 1 shows that at each of length L, if the energy increases, the number of neutrons produced increases. When increasing the length L double, 3 times, 4 times, 5 times the original length L (60 cm), the number of neutrons produced increases (Fig. 3). From the calculated results in Table 1 we compare neutron multiplicity at length of 60 cm with the results of YL Zhang et al. [8] (Fig. 4), and we found that our results are not suitable to the international result, that is because we have not considered the decline in intensity of proton beam through the lead when calculating in this model. The homogeneous model is only suitable for thin target. To improve, we use the screening effect model.

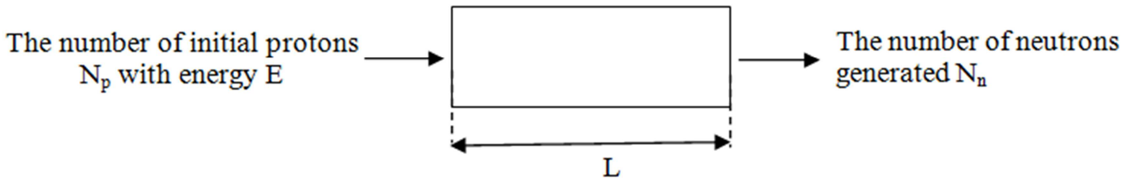


Fig. 2. A homogeneous model

Table 1. The number of neutrons produced at 9 incident energies of proton of the homogeneus model.

E (MeV)	5.1cmR – 60 cmL	5.1cmR – 120 cmL	5.1cmR – 180 cmL	5.1cmR – 240 cmL	5.1cmR – 300 cmL
200	5.0899E+17	1.0180E+18	1.5270E+18	2.0360E+18	2.5449E+18
250	2.7043E+18	5.4087E+18	8.1130E+18	1.0817E+19	1.3522E+19
350	2.9482E+18	5.8965E+18	8.8447E+18	1.1793E+19	1.4741E+19
500	3.3517E+18	6.7034E+18	1.0055E+19	1.3407E+19	1.6759E+19
600	3.5622E+18	7.1244E+18	1.0687E+19	1.4249E+19	1.7811E+19
700	3.7175E+18	7.4350E+18	1.1152E+19	1.4870E+19	1.8587E+19
800	3.8511E+18	7.7022E+18	1.1553E+19	1.5404E+19	1.9255E+19
1000	4.0143E+18	8.0286E+18	1.2043E+19	1.6057E+19	2.0072E+19
1500	4.2022E+18	8.4043E+18	1.2606E+19	1.6809E+19	2.1011E+19

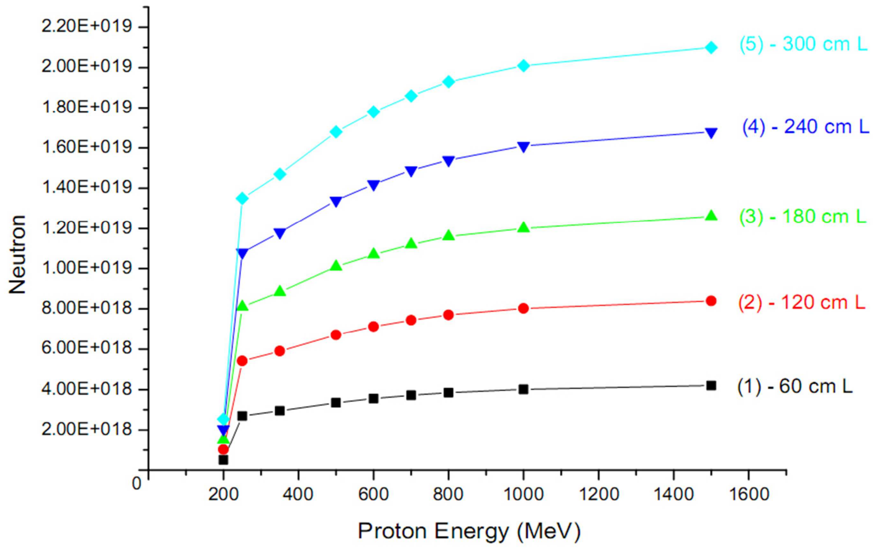
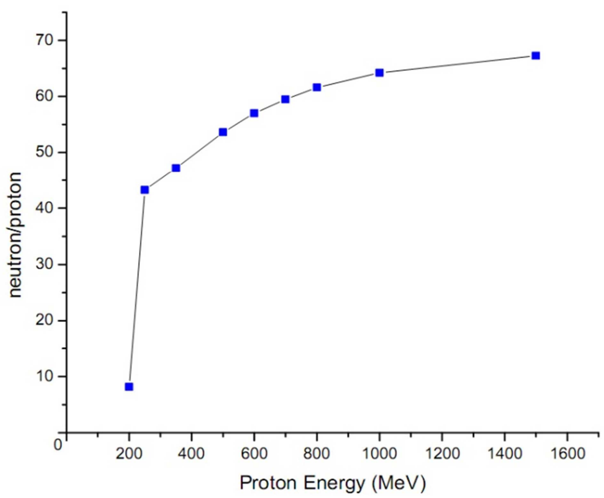
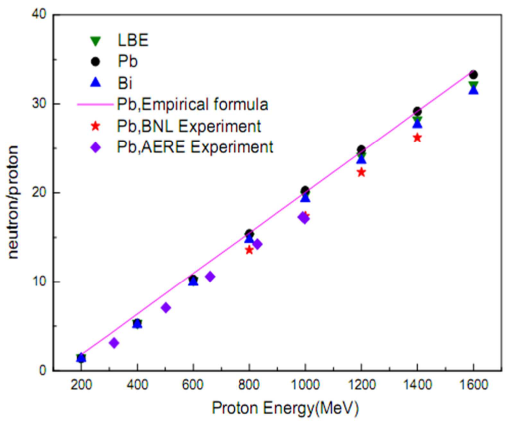


Fig. 3. The number of neutrons produced at 9 incident energies of proton in correspondence with the lengths L = 60 cm (1), 120 cm (2), 180 cm (3), 240 cm (4), 300 cm (5) of the homogeneous model.



(a)



(b)

Fig. 4. Neutron multiplicity at length of 60 cm between (a) our results in the homogeneous model and (b) Y L Zhang et al.

2.2. Screening Effect Model

The above homogeneous model is an approximation because when protons pass through the layers of lead, they lose energy and decline in intensity... To calculate closer than the physics picture, we take into account screening effect (Fig. 5).

We divided block of lead into n thin layers, each layer has a thickness d, all layers are divided by the energy jump from JENDL/HE library. In each layer we calculate the energy loss of proton through the lead, this energy loss can be calculated from Bethe-Bloch formula [13 - 17].

The incident energy of proton is E_0. The number of neutrons produced in the first layer is N_{n1}. When proton passed through the first layer, proton energy reduced to E_1 – incident energy at the second layer, at that time the number of neutrons generated in the second layer is N_{n2}, in which

$$E_1 = E_0 - \frac{dE_0}{dx} \quad (3)$$

The process of interaction will continue, in the end the total of neutrons generated is $N_n = \sum_{i=1}^{n} N_{ni}$.

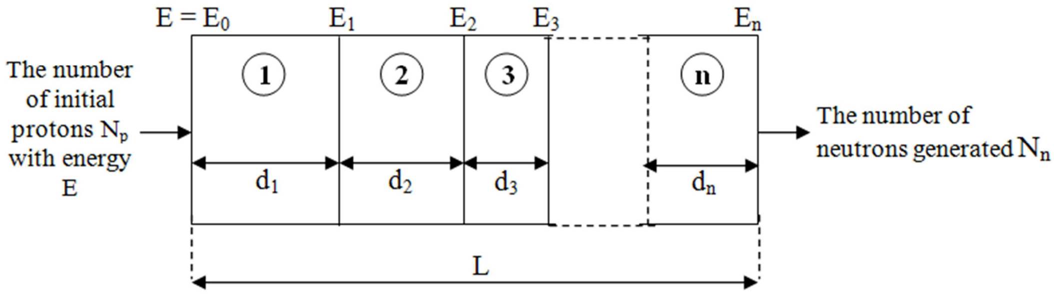


Fig. 5. *A screening effect model with energy levels:* $E_1 = E_0 - \frac{dE_0}{dx}$; $E_2 = E_1 - \frac{dE_1}{dx}$; $E_3 = E_2 - \frac{dE_2}{dx}$; $E_n = E_{n-1} - \frac{dE_{n-1}}{dx}$

In this work, with the screening effect model we calculate the number of neutrons produced at 9 incident energies of proton from 200 MeV to 1500 MeV (Table 2).

Table 2 shows that at each of length L, if the energy increases, the number of neutrons produced increases. However, when increasing the length L double, 3 times, 4 times, 5 times compared with the original length L (60 cm), the number of neutrons produced increases insignificantly (Fig. 6). This is because the length 120 cm, 180 cm, 240 cm, 300 cm has exceeded the range of proton in lead [13 - 17] (Table 3). Besides, as mentioned above we did not consider the influence of the other materials in the reactor such as fuel, structural material, moderator, absorber ...., especially we did not consider scattering of proton as well as (p,n) reaction itself.

On the other hand, the data in Table 2 also shows that the neutron multiplicity at the length of 60 cm is quite consistent with the result of YL Zhang et al. [8] on behavior and neutron multiplicity produced from liquid lead and it is more dominant compared with the result from [8] (Fig. 7).

Table 2. *The number of neutrons produced at 9 incident energies of proton of the screening effect model.*

E (MeV)	5.1cmR – 60 cmL	5.1cmR – 120 cmL	5.1cmR – 180 cmL	5.1cmR – 240 cmL	5.1cmR – 300 cmL
200	5.4894852401E+16	5.5205492401E+16	5.5516132401E+16	5.5826802401E+16	5.6137402401E+16
250	1.4630909453E+17	1.4659025453E+17	1.4687140453E+17	1.4715251453E+17	1.4743371453E+17
350	3.6142450789E+17	3.6164486789E+17	3.6186522789E+17	3.6208558789E+17	3.6230591789E+17
500	7.2691279281E+17	7.2705298281E+17	7.2719318281E+17	7.2682136281E+17	7.2747357281E+17
600	9.0838130216E+17	9.0848108016E+17	9.0858087016E+17	9.0868065016E+17	9.0878043016E+17
700	1.0636210750E+18	1.0636904890E+18	1.0637599070E+18	1.0638293170E+18	1.0638987270E+18
800	1.1932665952E+18	1.1933140542E+18	1.1933615182E+18	1.1934089782E+18	1.1934564382E+18
1000	1.5526874394E+18	1.5527088450E+18	1.5527302510E+18	1.5527516560E+18	1.5527730620E+18
1500	2.9379050000E+18	2.9858099273E+18	2.9858125109E+18	2.9858150946E+18	2.9858176783E+18

Table 3. *Range of proton in liquid lead at 9 energy levels.*

E (MeV)	Range of proton in liquid lead (cm)
200	4.82
250	6.96
350	11.98
500	20.88
600	27.47
700	34.44
800	41.70
1000	56.86
1500	96.82

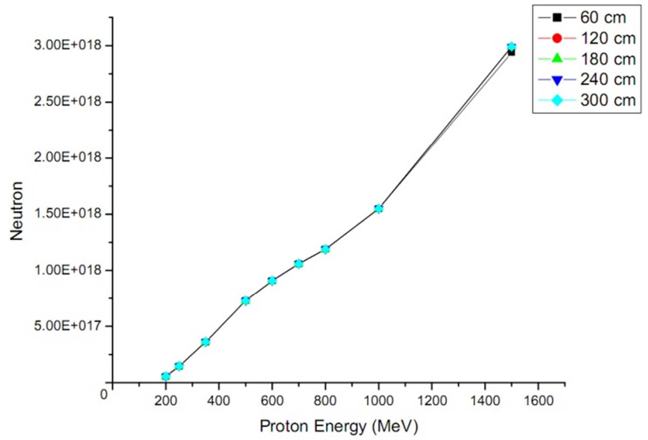
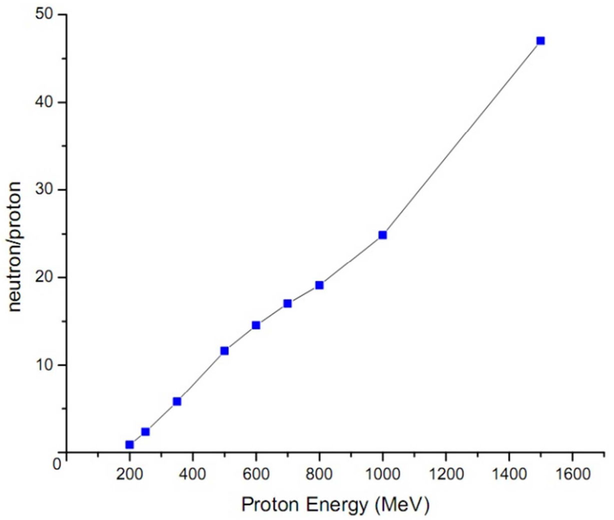
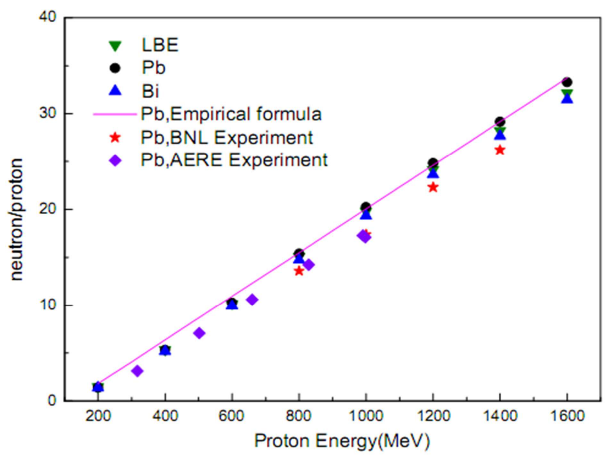


Fig. 6. *The number of neutrons produced at 9 incident energies of proton in correspondence with the lengths L = 60 cm, 120 cm, 180 cm, 240 cm, 300 cm of the screening effect model.*



(a)



(b)

Fig. 7. *Neutron multiplicity at length of 60 cm between (a) our results in the screening effect model and (b) Y L Zhang et al.*

From the above calculations, we find that in the future the design of an ADS without the separate spallation target is completely possible.

3. Conclusion

With the database of JENDL/HE, we have calculated the number of neutrons produced from (p,n) nuclear reaction at 9 incident energies of proton from 200 MeV to 1500 MeV in correspondence with different lengths of lead. The above calculations have led to the following conclusions:

1) When using liquid lead which makes the coolant as well as the spallation target for (p,n) reaction, the number of neutrons produced is not less than those produced by the method in which lead is used as the target in a conventional way.

2) So, it is possible to build the ADS model using liquid lead which makes the coolant as well as the spallation target.

To complete this idea, in the future works, we will continue to take into account the effects due to the heterogeneity caused in the reactor.

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