A Photo-neutron Source for a Sub-Critical Nuclear Reactor Program

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Abstract. Experiments to benchmark photo-neutron production calculations for an Accelerator Driven Sub-Critical System (ADS) are described. A photo-nuclear based neutron source with output > 10¹³ n/sec has been proposed as a driver for a program using the sub-critical assembly at Idaho State University. The program is intended to study ADS control issues arising from coupling an accelerator neutron source with a sub-critical assembly. The experiments were performed using the 20 MeV electron linear accelerator at the Idaho Accelerator Center (IAC). Results of calculations, that were made using ACCEPT, PINP, MCNP, and MCNPX codes to optimize photo-nuclear based neutron conversion targets, are compared to experimental data for a single energy measurement.

INTRODUCTION

Accelerator Driven Sub-Critical System (ADS) has been proposed[1,2,3] as a scheme to transmute nuclear waste. The ADS concept consists of an accelerator, a target module and a sub-critical blanket (which may contain spent fuel). The idea is to couple an accelerator with a subcritical system and produce neutrons, through (p, n) spallation reactions at proton energies ~1GeV, to transmute transuranic (TRU) isotopes (plutonium and minor actinides) and long-lived fission products into short-lived radioisotopes or stable nuclei for the possibility of closing the fuel cycle [4].

The effort at Idaho State University is to couple an electron linac of energy >20 MeV with an available subcritical assembly to study the ADS control issues arising from this coupling. In this case the neutrons are generated via photo-nuclear reactions. The electron beams, from the Linac, with energy greater than the neutron emission threshold energy are incident upon a thick target and induce bremsstrahlung radiation inside the target which in turn produces (γ, n) reactions.

This paper presents calculations carried out with the intention of optimizing the composition and geometry of conversion targets for maximum neutron production. Results of preliminary benchmark measurements are also given. Our calculations were made for beams of monoenergetic electrons incident perpendicularly on the target. ACCEPT, PINP, MCNP, and MCNPX codes were used to simulate the resulting electron – photon – neutron cascade in the target. The total neutron yields from targets bombarded by electrons were calculated as a function of electron energy, for the range 15 to 60 MeV, for lead and uranium targets. Our work extends the calculations to a variety of target materials, shapes and dimensions. Photo-neutron production was experimentally studied using a linear electron accelerator located at the Idaho Accelerator Center (IAC). The Linac served as the source of electrons with energies variable from 15 to 22 MeV. Measurements were performed on lead targets with different shapes and showed good agreement with the calculations.

METHOD AND CALCULATIONS

Electron, photon and neutron transport calculations are usually conducted using the Monte Carlo code, MCNP. This code takes into account most of the interactions of electrons, photons and neutrons with matter. However, photonuclear reactions are not taken into account. Therefore, for simulating the (γ, n), (γ, 2n) and (γ,f) processes, PINP (Photon Induced Neutron Production) code, was used. From the bremsstrahlung photon spectrum determined with the ACCEPT code, PINP calculates the photo-neutron production. An alternative way to obtain the photo-neutron yield is to run MCNPX, which is a new version of MCNP that takes the photo-neutron process into account. We have used these two ways to obtain the number of neutrons produced per incident electron. The calculated neutron production rate R is then given by the equation

\[ R(s^{-1}) = \frac{I}{Q} \int_0^\tau r \]

in which, I is the electron peak current (A), Q is the
electron charge (C), f is the repetition rate (s\(^{-1}\)), \(\tau\) is the pulse width (s), \(r\) is the photo-neutron production efficiency (neutron/electron).

We have simulated the photo-neutron production for different electron energies and different target materials, shapes and dimensions. The total neutron yields from targets bombarded by electrons were calculated as a function of electron energy, for the range from 15 to 60 MeV. Figure 1 shows the calculated photoneutron yield (Neutrons/Sec.KwMeV) as a function of the incident electron energy, for lead and uranium targets having the same dimensions. It can be seen that for the electron energy > 40 MeV there is no significant increase in the neutron yield.

One way to improve the neutron yield from a target is to reduce the amount of electron and photon losses due to the scattering at the target surface. This can be done by considering a target with a hole drilled up to a certain depth and having the electron beam hit inside the hole as illustrated in figure 3.

The calculations were performed for different target thicknesses, for 40 MeV incident electron energy, to find the optimum irradiation position for each. The results show that the optimum irradiation position is always in the middle of the target regardless of its thickness as can be seen from figure 5.

![FIGURE 1](image1.png)

**FIGURE 1.** Neutron yield as a function of incident electron energy for Pb and U targets.

The dependence of the neutron yield on the target thickness, for incident electron energy of 20 MeV, is shown in figure 2. There is no significant increase in the neutron yield for the target thickness greater than 10 cm, for Pb and U targets, at this particular energy.

![FIGURE 2](image2.png)

**FIGURE 2.** The neutron yield as a function of the target thickness for lead and uranium.

![FIGURE 3](image3.png)

**FIGURE 3.** The irradiating position (a) On the target surface. (b) Inside the hole in the target.

For constant target thickness and variable irradiation point inside the target to different depths, we obtained the neutron production curve of Fig. 4. Note that the irradiation point, inside the hole, in the middle of the target is the optimum position for 10 cm thick target.

![FIGURE 4](image4.png)

**FIGURE 4.** The dependence of the value of the neutron yield on the irradiation position inside the target at 20 MeV.
FIGURE 5. The neutron yield as a function of the irradiation position for different target thickness irradiated at 40 MeV.

Since the photonuclear-based neutron source with output $> 10^{13}$ n/sec is required as a driver for the proposed program using the sub-critical assembly, we have calculated the required average power in kW to generate this number at various electron energies. Figure 6 shows the dependence of the required power on the incident electron energy.

FIGURE 6. The required power (kW), to produce $5 \times 10^{13}$ n/s, as a function of the incident electron energy.

EXPERIMENTAL SETUP AND MEASUREMENTS

Photo-neutron measurements were carried out using a pulsed electron linac located at the Idaho Accelerator Center (IAC). The electron pulse width is 2 µs with 60 Hz repetition rate. The particular accelerator used delivered electrons with energy in the range (15 – 22 MeV). The corresponding electron peak currents were in the range (30 – 80 mA).

Our target was a lead cylinder with a 5 cm diameter and 10 cm length. The target was divided into five small cylinders, between which, lead foils of the same diameter were placed. Thus, lead foils were distributed along the target length and having the same diameter of the target, allowed the axial and lateral distribution of the neutron yield to be measured. Sufficient activity in the foils was obtained in about 20 min. Another lead target of the above dimensions was prepared with a hole drilled up to the middle of its length, to examine this geometry as well.

To obtain the neutron production, the foils were taken immediately after irradiation to a gamma spectrometer to measure the $\gamma$- rays yield emitted from the $^{203}$Pb isotope. The photo-nuclear reaction, $^{204}$Pb ($\gamma$, n) $^{203}$Pb, on the isotope $^{204}$Pb, produces $^{203}$Pb which can be detected by its characteristic $\gamma$- ray of 279 keV. The gamma spectrometer consists of a high purity germanium (HPGe) detector, an amplifier and a multichannel analyzer interfaced to a PC for data processing. The total and photo peak efficiencies of the detector were determined by using Ba-133 source which had an activity of 42.96 KBq.

Figure 7 shows the measured spectrum from a lead foil counted after irradiating the target with the 20 MeV electron beam for 20 min.

FIGURE 7. The obtained spectrum for the $\gamma$- ray (279 keV) emitted from the foil

Using the measured $\gamma$- ray yield, the neutron yield can be calculated by taking into account the detector efficiency, the abundance ratio of the lead isotopes and the volume ratio between the foils and the target. The measured neutron production rate from 20 MeV electron Linac was $10^{11}$ n/s with an error of about 20% which is in good agreement with the calculated value from the simulation.
CONCLUSION

High neutron yields can be achieved through the use of an electron accelerator. They reach the values on the order of $\sim 10^{12}$ n/s.kW in the case of lead target and can be doubled with the hole geometry. In order to increase the neutron number it is necessary to increase the incident electron beam energy and power. Calculations were compared with preliminary experimental data for lead targets at 20 MeV and agreement was satisfactory giving confidence in the calculations. These results have useful implications in the development of the photonuclear-based neutron source as a driver for accelerator/subcritical assembly.

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