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# DESIGN OF A TARGET AND MODERATOR AT THE LOS ALAMOS SPALLATION RADIATION EFFECTS FACILITY (LASREF) AS A NEUTRON SOURCE FOR FUSION REACTOR MATERIALS DEVELOPMENT

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**ABSTRACT:** The LASREF facility is located in the beam stop area at LAMPF. The neutron spectrum is fission-like with the addition of a 3% to 5% component with E > 20 MeV. The present study evaluates the limits on geometry and material selection that will maximize the neutron flux. MCNP and LAHET were used to predict the neutron flux and energy spectrum for a variety of geometries. The problem considers 760 MeV protons incident on tungsten. The resulting neutrons are multiplied in uranium through (n,xn) reactions. Calculations show that a neutron flux greater than $10^{19}$ n/m$^2$/s is achievable. The helium to dpa ratio and the transmutation product generation are calculated. These results are compared to expectations for the proposed DEMO fusion reactor and to FFTF.

**KEYWORDS:** fusion, irradiation facility, LAMPF, LASREF, Monte Carlo

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## INTRODUCTION

The Los Alamos Meson Physics Facility (LAMPF) produces a 1 mA beam of 800 MeV protons. The proton beam is delivered to the Los Alamos Spallation Radiation Effects Facility (LASREF) where neutrons are generated as the protons interact with the isotope production targets and copper beam stop. LASREF has been used to study basic radiation damage mechanisms and to aid materials selection in support of fusion reactors, accelerators, and the Accelerator Transmutation of Waste (ATW) project.

The LASREF neutron flux and energy spectrum in the current configuration was calculated [1] using the Monte Carlo based codes LAHET and HMCNP [2], which is a modified version of the code MCNP [3].

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For neutrons with E > 1 keV, the flux was determined to be 5.5E+17 n/m$^2$/s [4]. The calculations were confirmed by activation foil measurement and spectral unfolding using a version of the code STAY'SL [5] which has been modified to accommodate neutron energies up to 800 MeV. The measured neutron flux was 4.6E+17 n/m$^2$/s for neutrons with E > 1 keV [6]. Each experiment at LASREF currently includes a set of activation foils to measure the incident neutron flux and energy spectrum.

The current LASREF flux level is sufficient for basic radiation damage studies, accelerator materials development, and fusion reactor diagnostic systems tests [7]. However, a higher flux is needed to study fusion reactor first-wall materials and the ATW target-blanket system. Previous calculations [8] have [illegible]n that it is possible to increase the LASREF flux to 4.2E+18 n/m$^2$/s [illegible] [illegible]ing the target radius and changing the beam stop material from copper to tungsten. The purpose of this paper is to present the results of continued work to increase the LASREF flux and to simulate the damage expected at a fusion reactor.

## LASREF GEOMETRY

The current LASREF configuration is shown in Fig. 1. The proton beam strikes the targets in the isotope production facility first and then comes to rest in the copper beam stop. Neutron irradiations take place in the indicated areas. Eight of the twelve available irradiation inserts are shown. For this configuration, the neutron flux was measured to be 2.8E+17 n/m$^2$/s [6]. With the isotope production targets removed, the measured flux was 4.6E+17 n/m$^2$/s [6]. The copper beam stop was designed with a radius of 10.5 cm to accommodate the radial Gaussian beam profile with $\sigma$ = 2.5 cm, where $\sigma$ is the standard deviation.

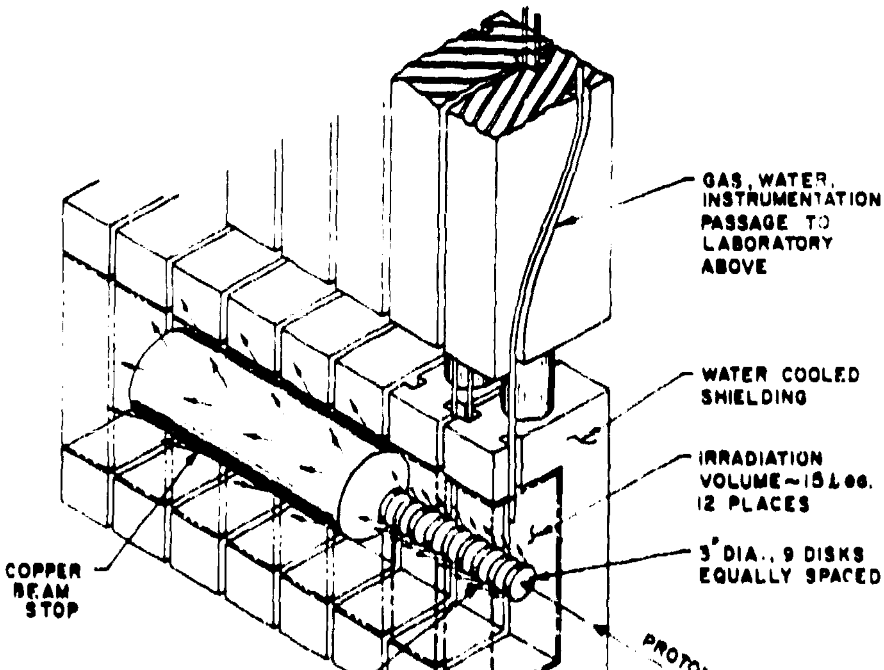


Fig. 1. Diagram of the current LASREF configuration.

**RESULTS**

Fig. 3 shows the effect of the uranium ring around the target. The neutron surface flux at a radius of 6.25 cm is shown for the tungsten target (r=5.25 cm), the tungsten target (r=4.25 cm) with 2 cm of $^{238}$U, and the tungsten target (r=4.25 cm) with 2 cm of $^{235}$U. The tungsten target with r=5.25 cm is the baseline for comparison for this study. The addition of the $^{238}$U was intended to increase the flux through fast fission, but was unsuccessful due to the small fast fission cross section. The addition of the $^{235}$U increased the neutron flux through thermal fission. The scalar flux values are given in Table 1. The $^{235}$U is shown to increase the scalar flux by a factor of 3. Fig. 4 shows how the scalar flux varies along the beam stop for the tungsten target (r=4.25 cm) with 2 cm of $^{235}$U around the target. The flux was averaged over lengths of 5 cm. A length of 10 cm along the beam stop is shown to be at an average flux over $10^{19}$ n/m$^2$/s. To determine the effect of the uranium enrichment on the scalar flux, two additional runs were made with enrichments of 30% and 70%. The plot of scalar flux versus enrichment is given in Fig. 5 along with a least squares fit to the data. The equation fits the data with $r^2$=0.999. Using the equation, a flux greater than $10^{19}$ n/m$^2$/s/mA requires the uranium enrichment to be greater than 83%.

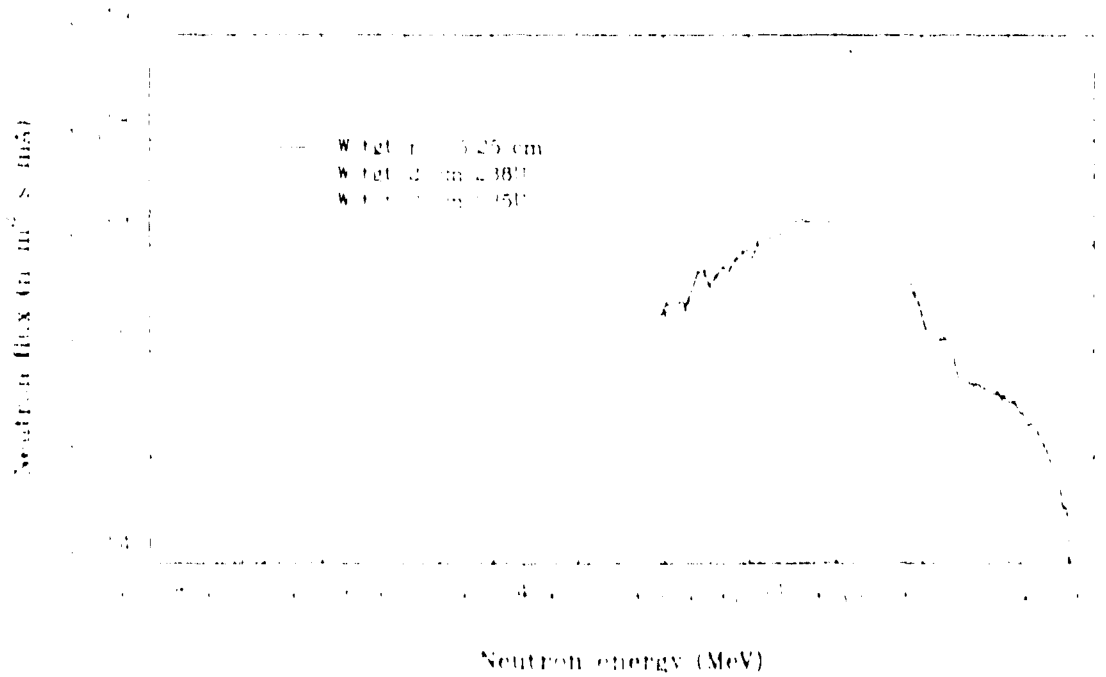


Fig. 3. Neutron flux at r = 6.25 cm averaged over a length of 5 cm.

Table 1. Scalar neutron fluxes for beam stop with 2 cm uranium ring.

| beam stop configuration | scalar flux at r=6.25 cm (n/m$^2$/s) |
|---|---|
| W r=5.25 cm | 4.3E+18 |
| W r=4.25 cm, 2 cm $^{238}$U | 4.6E+18 |
| W r=4.25 cm, 2 cm $^{235}$U | 1.3E+19 |

Under typical operating conditions, $\sigma$ at LASREF is currently estimated to be 1.75 cm. Because $\sigma$ is now smaller than the original design value, the beam stop radius can be reduced. Previous calculations [8] explored the effect of reducing the beam stop radius to 5.25 cm and changing the beam stop material to tungsten. The isotope production targets were removed for this calculation and the results indicated that the neutron flux could be increased to 4.2E+18 $n/m^2/s$.

For this work, the effect of placing a ring of uranium around the tungsten target is explored. The beam stop was modelcd as a homogeneous mixture of 85% tungsten by volume and 15% water by volume. The beam stop radius was reduced from 5.25 cm to 4.25 cm to allow room for the uranium. A 2 cm thick ring of uranium was placed around the beam stop. The uranium was followed by 15 cm of SS 316 to allow for reflection of the neutrons. A schematic of the basic geometry used for this work is shown in Fig. 2. Note that the isotope production targets were also removed for this set of calculations.

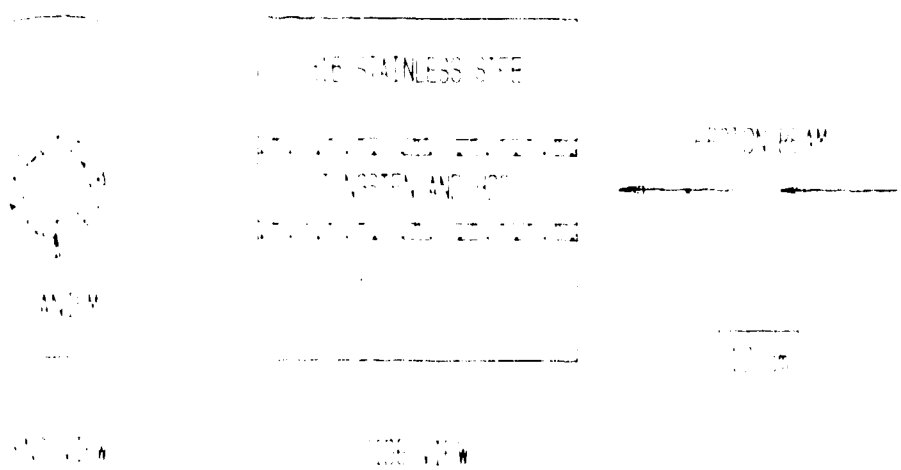

Fig. 2. Schematic of the primary LASREF geometry for the calculations.

**CALCULATIONS**

The LAHET calculations were carried out using the Bertini model of intranuclear cascade, as well as the preequlibrium model following the cascade. Because the proton beam interacts with graphite targets before the beamstop, the incident proton energy was taken to be 760 MeV to allow for some energy loss from the 800 MeV beam delivered by LAMPF. The beam spatial distribution was modeled as a Gaussian in the radial direction with $\sigma$ = 1.75 cm.

The calculations were carried out on an HP 9000/735. The number of incident protons used varied as needed to result in acceptable statistical uncertainty. The baseline target design for this study was taken from the previous work [8]. The baseline target consists of a tungsten beam stop with a radius of 5.25 cm. For the case of a 5.25 cm beam stop composed of 85% tungsten and 15% water target, $10^5$ protons were required. The incident protons created $10^6$ neutrons with $E < 20$ MeV that were transported by HMCNP. Over five hours of CPU time were required to complete this run.

To compare beam stop configurations, neutron surface flux tallies were computed for each run at radial distances of 5.25 cm and 6.25 cm, with spatial bins every 5 cm along the length of the beam stop. The values presented in this work refer to the highest calculated flux for each beam stop configuration at a given radial tally surface.

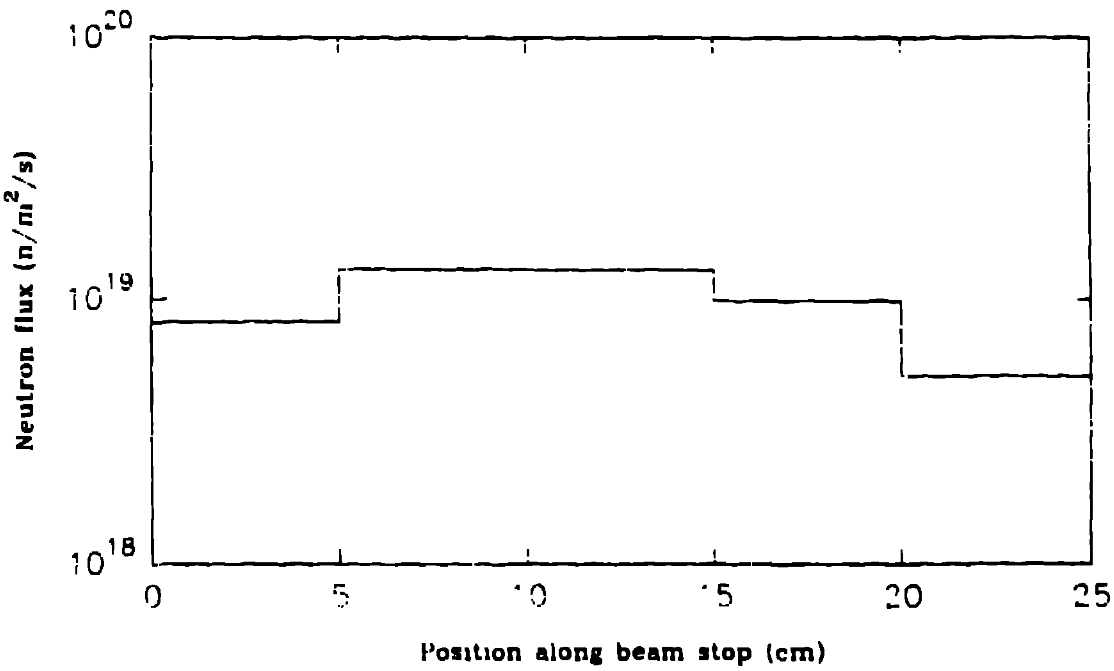


**Fig. 4. Scalar flux at r=6.25 cm versus position along a tungsten beam stop surrounded by 2 cm of $^{235}$U.**

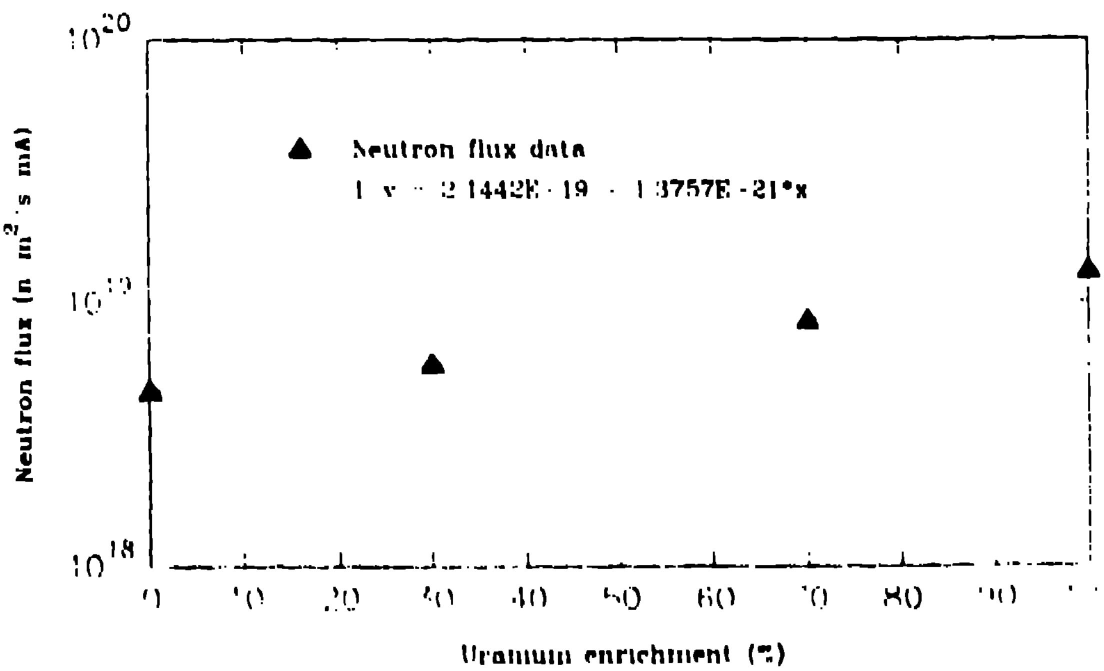


**Fig. 5. Scalar flux at r=6.25 cm versus enrichment for a 4.25 cm tungsten target surrounded by 2 cm of uranium.**

Additional calculations were performed to determine the effect of a void next to the uranium. The void space represents an area where experiments would be placed. The presence of the void is expected to decrease the flux due to the lack of neutron reflection by the void. For these runs, the target configuration consisted of the 85% tungsten beam stop (r=4.25 cm) surrounded by 2 cm of $^{235}U$. A void ring 5 cm thick was placed between the uranium and the 15 cm thick SS 316. A second computation considered the void space to be infinite (i.e. no SS 316).

The neutron spectra for these calculations are presented in Fig. 6. The effect of the void is substantial. Low energy neutrons that would normally be reflected back into the uranium and cause a fission event are not reflected by the void. The scalar flux is decreased by a factor of 2.5 when the 5 cm void is introduced. Making the void infinite reduces the scalar flux by a factor of 4. In order to maximize the neutron flux, experiments should be designed to be as dense as possible. Any unused experimental volume space should be filled with a material the reflects neutrons, such as beryllium.

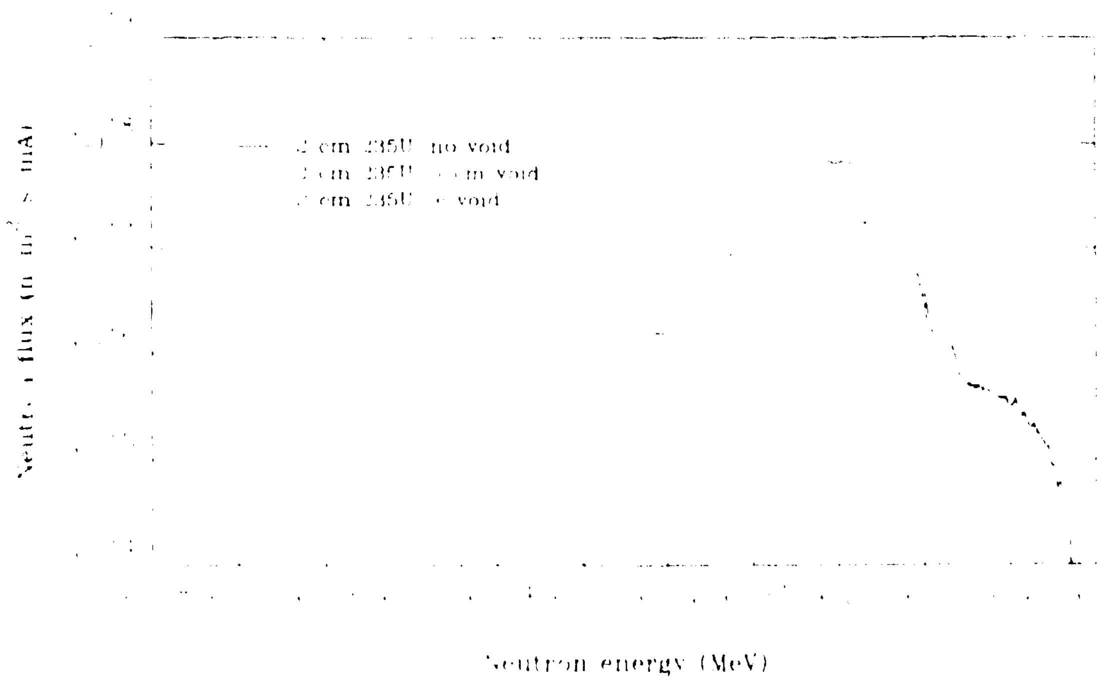


Fig. 6. Neutron flux at r=6.25 cm averaged over a length of 5 cm to demonstrate the effect of voids near the target.

The importance of the void indicates that a neutron reflector around the target may increase the neutron flux. Two calculations were performed using the tungsten target (r=4.25 cm) with 2 cm of $^{235}U$ surrounded by beryllium. For these calculations the beryllium thickness was 1 cm and 0.5 cm. The neutron flux was tallied at the beryllium surface in each case, since an experiment would be placed behind the beryllium. In each case less than a 10% improvement was achieved in the scalar neutron flux. The reflector does increase the number of neutrons produced, but because the flux falls off as 1/r in the radial direction, the penalty for placing additional material between the uranium and the tally surface is great. However, additional trials varying the beryllium and uranium thickness may show an increase in the flux.

Fig. 7 compares the calculated LASREF spectrum with the proposed fusion DEMO reactor [9] and the Fast Flux Test Facility (FFTF). The LASREF spectrum is based on the 4.25 cm radius tungsten beam stop surrounded with 2 cm of $^{235}U$. Fig. 7 shows that the upgraded LASREF target models the fusion DEMO reactor in total flux and in flux with E > 2 MeV. To compare the spectra for use in irradiating fusion reactor materials, the damage mechanisms must be considered. Using the cross sections developed by Wechsler, et al., [10], the helium production rate and the rate of atomic displacements in copper were calculated for the LASREF target operating at 1 mA. The calculated helium production rate is 2.8E-06 atomic parts per million (appm) helium/s and the calculated displacement rate is 8.2E-07 displacements per atom (dpa)/s, which gives a ratio of 3.4 appm He/dpa. A trade off exists between the total displacements and the helium to dpa ratio. As the flux and displacement rates increase, the helium to dpa ratio decreases and the spectrum becomes softer. The values presented for LASREF correspond to the maximum achievable displacement rate. The current LASREF facility produces a helium to dpa ratio of 18 [4]. For a 14 MeV neutron source, the helium to dpa ratio is 13 appm He/dpa, while the ratio for FFTF is below 0.3 appm He/dpa.

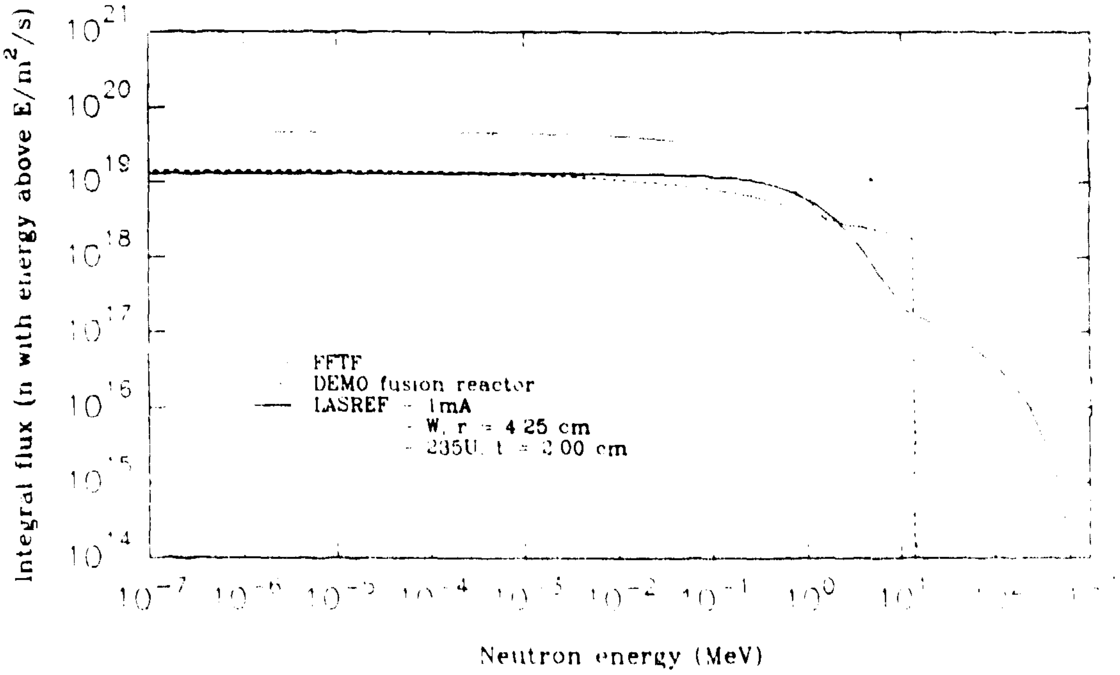


Fig. 7. Integral neutron flux comparison of LASREF, the fusion DEMO, and FFTF.

The transmutation product generation rates in a copper sample for the tungsten target (r=4.25 cm) with 2 cm of $^{235}$U at 1 mA due to neutrons with E > 20 MeV and protons with E > 1 MeV are given in Table 2. Similar calculations should be performed for the neutrons with E < 20 MeV for both the LASREF target and the fusion DEMO reactor. However, these calculations are not possible using LAHET and HMCNP due to the loss of information as the tally information is written by HMCNP.

Table 2. Transmutation product generation rates in copper for the tungsten target (r=4.25 cm) with 2 cm $^{235}U$ at 1 mA.

| Element | Production Rate (atoms/s/mA) |
|---|---|
| Ni | 4.6E+14 |
| Co | 2.9E+14 |
| Fe | 1.5E+15 |
| Mn | 1.3E+15 |
| Cr | 8.6E+14 |

## CONCLUSIONS

Calculations have shown that by changing the beam stop material to tungsten, reducing the radius to 4.25 cm, and surrounding the target with 2 cm of $^{235}U$, the LASREF neutron flux can be increased to 1.3E+19 n/m$^2$/s. The uranium enrichment can be reduced to 83% while the scalar flux is maintained at $10^{19}$ n/m$^2$/s. Void space in an experimental volume is a major concern and should be minimized. The calculated neutron flux and spectrum compare well with those expected at the fusion DEMO reactor. The helium to dpa ratio was calculated to be 3.4, which is lower than expected at a fusion source, but is higher than the ratios achieved at typical reactors.

## ACKNOWLEDGEMENTS

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