Characterizing the Fluence of WPI’s New Deuterium-Deuterium Neutron Generator

A Major Qualifying Project Report

submitted to the Faculty

of the

Worcester Polytechnic Institute

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

John Crespi

Brian Gardner

Date: April 30th, 20015

Approved:

Professor David Medich

Table of Contents

Table of Figures

Abstract

The Worcester Polytechnic Institute received a neutron generator which needed to be characterized. This project was created with the intention of accommodating the Radiation Lab's needs by optimizing and documenting the neutron generator's capabilities. This research project utilizes the topics of neutron activation and gamma spectroscopy to determine and improve the flux of the beam. The analysis of radioactive gold foils plays a crucial role in providing the data needed to evaluate the beam. Also included is an analysis of the effects of moderation on the fast neutrons produced by the neutron generator. The success of this project resulted in an optimized beam prepared for future WPI research.

Introduction

Worcester Polytechnic Institute has recently received a new neutron generator primarily to be used for research and experimentation pertaining to medical imagining. The secondary purpose of this purchase is to provide graduates and undergraduates of the lab with the ability to perform neutron dependent experiments such as determining scattering lengths and cross sections. There is a particular interest in using it to optimize neutron imaging for medical purposes and to allow graduate students to supplement their theses. Additionally there have been major steps taken to strengthen WPI nuclear program. Scholarships are now able to be provided to students who show interest and growth relating to nuclear science. New classes such as nuclear instrumentation courses have been created, and additional faculty have been hired to provide additional education opportunities. The purchase of the neutron generator is in part a reflection of the growing efforts to increase WPI's ability to stimulate Nuclear Science and Engineering students. Additionally, since WPI has a project based curriculum creating project opportunities for undergraduates is a priority. However all of these uses will assume that the generator is operating at its fullest capacity. Without ensuring the beam is producing neutrons to the best of its ability it is impossible to be able to verify the best results for subsequent projects. As delicate and newly assembled piece of equipment it is difficult to guarantee optimal results using just the initial diagnostic tests run by the manufacturer. Additionally being a new piece of equipment there is a temporary knowledge gap regarding to best tune the machine to reach these best results. In order to insure that the machine is prepared for future projects and to learn about the operation of the neutron generator experiments must be carried out to test the state of the neutron beam. To accomplish this goal the flux of the beam must be calculated. This project achieves this goal through researching and experimenting with the activation of gold foil and subsequent gamma spectrometry. Tuning is preformed alongside the manufacturer and improvements to the beam are made based on these results. The project presented in this paper is the process through which these experiments were selected and performed with the intention of learning about and optimizing the neutron beam.

Background

Generator Characteristics

The generator that we used for this project is a portable generator that operates using deuterium-deuterium fusion. A deuterium beam is accelerated and aimed at a deuterium target using plasma. The plasma is controlled by a high voltage electric field. When the deuterium ions are given enough energy by the plasma to produce fusion when they collide with the deuterium target Helium-3 isotopes and neutrons are created. The neutrons tend to recoil in every direction after the collision but tend to move for a little more often than the other directions because of the initial forward momentum. Finally the neutrons are ejected through the front of the generator in a beam. The manufactures expect a beam fluence of 1E7 n/cm^2/s is possible. The neutrons exit the generator at an energy of 2.5 MeV which is classified as a "fast neutron." Fast neutrons are so energetic that they are not absorbed by most materials. To solve this issue there is a moderator in front of the beam which slows them down to the thermal range. The moderator slows the neutrons to the thermal range through elastic collisions with nuclei. At the thermal range the kinetic energy of the neutron is at equilibrium with room temperature, about $7°C$. At this energy range the neutrons are much more likely to be absorbed making them useful for neutron activation.

Medical Imaging

WPI's new neutron generator is intended to be used for medical imaging. Medical imaging is the act of using various methods such as radiology to obtain images of a patient's body which would otherwise be obscured by tissue or bone. Medical imaging has become a staple of modern medicine by increasing the accuracy of diagnoses. Ultrasonography and radiography, now common practices are both the product of progressing medical imaging. Further advances in the field can only improve doctor's ability to cure illness.

Current imaging techniques fall into two categories, there are ones with high resolution but have a long exposure time and ones that have a short exposure but low resolution. Examples of the first kind are techniques such as PET or X-rays CT scans. The PET (positron emission tomography) scan consists of introducing a tracer into the bloodstream and then monitoring where it builds up by detecting the gamma rays produced by it. X-ray scanning, on the other hand, uses computer produced X-rays to collect images at a certain depth. When analyzed around a given axis of rotation 3D images can be compiled from the 2D images. This process is what happens inside CT machines. These techniques can take a significant amount of time to set up and performed depending on which part of the body needs to be scanned. with Techniques that have a low spatial but high visual resolution are things like MRIs. MRI's use a strong magnetic field to cause hydrogen atoms within the body to produce radiowaves. Studying the radio frequency can produce an image of the body's different tissues can be formed. MRIs are one of the techniques that have a high enough time resolution to take images of body systems while they are in operation. However MRIs have a very low spatial resolution.

Neutron imaging has the potential to revolutionize medical imaging techniques as it can provide much sharper images than using x-rays. Where x-ray imaging depends on the overall density of the material which the rays are passing through, neutron imaging depends upon the atomic composition of the material. The neutrons will penetrate heavier elements but will interact with lighter elements such as hydrogen. X-rays provide good images of bone due to its density, but since neutrons interact very strongly with hydrogen atoms they can be used to examine body tissues with great effectiveness. Neutron imaging has the advantage of potentially having very high length resolution and producing an image in a short period of time. These advantages exist in part because neutrons are not charged. This attribute however is a main reason why the neutrons hard to detect directly. One possible method for detecting the neutrons explored in this project is by activating gold foils and measuring how radioactive the foils are.

Neutron Activation

In order to predictably use a beam of neutrons for scientific measurements and experiments the beam needs to be characterized. In order to characterize the neutron beam various aspects of the beam need to be documented. Of particular interest are the density of the neutrons in the beam and the energies of those neutrons. However, in order to gain this information a proper technique for detecting neutrons needs to be selected. Neutrons pose a number of problems to standard detection methods because unlike electrons and protons they have no electric charge. However, neutrons do have a magnetic dipole moment though it is too small to be measured using conventional methods and therefore cannot be easily utilized for neutron detection. Additionally, it is predicted that neutrons have an electric dipole moment but it has yet to be observed so it too cannot be used to detect neutrons. It is these properties of the neutron that make it difficult to directly detect, instead other techniques must be used.

An efficient strategy is trying to study the neutrons based on their effect on the materials with which they interact with rather than attempting to directly study them. This yields much better results. Neutrons are fairly massive particles with a mass of 939.56 MeV/c2 and can carry enough energy with them to excite nuclei during a collision. There are three primary ways of detecting the effects that neutrons have on other materials. The first possible method of neutron detection is absorptive reactions which is when a neutron collides with an atom such that it splits into two smaller atoms. There are only a few atoms that are useful for this method, namely Boron and Lithium because they are the only nuclei that readily split when hit by a low energy neutron. The new nuclei released in the collision have enough energy to ionize the air around them and it is this ionization that is measured. This method is primarily used for electrons with a low energy. Another common way of detecting neutrons is through elastic scattering reactions. This method utilizes the momentum of a high energy neutron as it impacts a nucleus and measures the transferred energy. Materials used for this are typically hydrogenous because the most energy is transferred when the mass of the two particles are the same. This technique is used for high energy neutrons. The third common method for thermal neutron detection is neutron activation. Through this process a material absorbs a neutron both increasing the mass of the nucleus and exciting it, thereby making a new isotope. This new isotope of the material must be radioactive for it to be considered neutron activated. This nucleus then decays back to a stable state through gamma or beta emission over half times that vary from fractions of a second to thousands of years. Neutron activation is the only common way for a stable material to be made radioactive. There is a wide variety of possible materials usable for neutron activation, which all share the same two characteristics, they have a large cross section for neutron absorption and they only absorb neutrons over a small range of energies. Neutron activation is particularly useful for low energy (thermal neutrons).

A standard way to activate a material is through placing it in the path of the neutron beam. Depending on the intensity, the exposure time, and the energy of the beam a material will gain a certain amount of radioactivity. The longer the exposure, more intense the beam, and higher the absorption cross section is at the beam energy the stronger the radiation will be. The radioactive emissions can be measured and used to provide valuable information both about the density of neutrons and the composition of the otherwise nonradioactive materials. The radioactive spectra emitted after this process can be matched with known spectra to determine the makeup of the material without destroying it. Alternatively, by analyzing a pure material important information about the incident beam of neutrons can be calculated such as the flux.

For thin samples of carefully selected elements the equations behind neutron activation are fairly straight forward. The thermal neutrons will be absorbed by the sample nuclei and cause a new isotope (A+1,Z) of the same element but in an excited state to be formed. This new isotope will decay through gamma emission to the ground state with a standard half-life of $T_{1/2}$. Using the half-life the decay constant can be determined through the definition:

$$\lambda = \frac{ln(2)}{T_{1/2}} \qquad \text{Eq. 1}$$

The radioactive nuclides decay at a rate of:

$$\frac{dN(t)}{dt} = -\lambda N \qquad \text{Eq. 2}$$

And stable nuclides are activated at a rate ,"R":

$$R = \Phi\sigma \qquad \text{Eq. 3}$$

where Φ is the fluence of neutrons and σ is the chance of a neutron being absorbed.

Therefore the activity of a sample at a given time is:

$$A(t_1) = N(t_1)\lambda = N_0 R(1 - e^{-\lambda t_1}) \qquad \text{Eq. 4}$$

Gold Activation

The neutron generator we will be characterizing emits neutrons in the thermal energy range. Therefore we selected gold for our target materials as it has strong neutron absorption across for neutrons in the thermal range. Gold also has a number of other characteristics that make it a strong candidate for the target material. It has a large neutron cross section meaning that it is likely to capture a neutron that it interacts with. Gold also has only one natural isotope (Au 197) which will make it so that it is only common excited to one state (Au 198). The last advantage of gold is that (Au 198) has moderate halftime of 2.696 days which is advantageous for several reasons. First, the half life is short enough that the gold will definitely be stable by the time they are used since they have been unused for months. Second, the half-life is long enough that an excessive amount of activity will not be lost between irradiation and analysis. Third, the half life is short enough that gamma spectrum analysis can be performed in a reasonable amount of time. All of these factors combine to make gold an ideal target material for the neutron activation experiments that we will be conducting.

Gamma spectroscopy

In order to properly study the radiation emitted from an object the proper technique and equipment is required. Spectroscopy is the study of the way radiated energy and matter interact. Using a spectrograph several properties of radiation can be tracked over a period of time, including the intensity which is particularly useful for our purposes. Unsurprisingly, spectrographic data is best represented using a spectrum plot which tracks a particular variable as a function of the energy of radiation. There are many different types of spectroscopy that utilize different forms of radiation. To determine the flux of the beam gamma spectroscopy will be used because neutron activated gold emits gamma radiation. In order to calculate the activity of a neutron activated sample the number of gamma rays incident upon the detector and their energies should be recorded. Through simple calculations this data can be used to calculate the number of neutrons which interacted with the gold samples, thereby providing the flux of the beam.

Gamma spectroscopy is a method of spectroscopy that measures the gamma radiation from a material. It specifically measures the number of gamma rays at various energies. This technique is useful for determining the number of gamma emitting nuclides within the source material. The higher the number of gamma rays detected the more gamma emitters there are in the source. Different source materials have different energy gamma emissions. During neutron activation of gold, a beta particle with a maximum energy of 961 keV is released, following that a gamma ray with a maximum energy of 412 keV is released. The total activity of the gold sample once activated is:

$$A \equiv \frac{dN}{dt} \qquad \text{Eq. 5}$$

Simply enough the count rate of gamma rays can be expressed by the following equation:

$$n_\gamma = \epsilon_\gamma A \qquad \text{Eq. 6}$$

The “n_γ” in the equation is the number of gamma rays detected and the “ϵ_γ” is the probability that the detector will see the gamma ray.

Using Gamma Spectroscopy to Determine Neutron Flux

The data obtained from the gamma spectrometer can be used to calculate the flux of the neutrons using equations 4, 5, and 6 the activity of a sample based on gamma spectroscopy is:

$$A(t) = \frac{\lambda C}{\epsilon(1 - e^{-\lambda t_0})(e^{-\lambda t_1} - e^{-\lambda t_2})} \qquad \text{Eq. 7}$$

Where t_0, t_1, t_2 are the time ending irradiation, the time that counting began, and the time counting ended respectively. Referring back to expectations of neutron activation, all of the properties of gold are known except the activity. Once the activity is calculated it can be utilized to solve for the neutron flux with the following equation:

$$\Phi = \frac{A(t)}{\lambda \sigma N_0 t_0} \qquad \text{Eq. 8}$$

Methodology

This project set out to achieve two goals, the primary goal was to characterize and optimize the fluence of the neutron beam from WPI's new D-D neutron generator. The second goal of the project was to observe the effectiveness of polyethylene as a neutron moderator. A series of neutron activations of gold foils were conducted to achieve these goals.

Fluence Optimization and Characterization

The main goal of this project was to optimize and characterize the neutron fluence from the D-D neutron generator. To do this a set of four steps were devised. The first was to locate the position of the beam on the generator, then to measure the neutron fluence within the beam. Once this was done the beam was to be tuned and then the new fluence was to be determined. Lastly backscattering of neutrons was to be done so that the fluence after the tuning was complete could be compared to the fluence reported by the manufacturer. With this set of steps the beam could be successfully tuned and the neutron flux could be optimized and characterized.

The first step in determining the neutron flux was to find the beam. This was achieved by placing foils in a foil holder with a spacing between foils of 2.5 cm covering a rectangle of size 15cm by 25cm. Such a spacing was chosen because a large area had to be covered to find the location of the beam on the generator. The foils were selected to be of similar mass so only a difference in counts had to be determined and the activity did not need to be calculated. The expected fluence of the beam was $1\text{-}2*10^7$ with backscatter so the foils were irradiated for 180 minutes to yield an expected activity of ~2000 Bq**.** This trial in which the beam spot was located set up the team for further experiments to determine and optimize the fluence of the neutron beam.

Once the beam spot was found the next step that the team took was to determine the un-tuned beam fluence. To do this an approximation of a circle was placed in the area of highest fluence. The circle was of a radius of 7.5 cm which thoroughly covered the area of highest fluence determined by the previous experiment. The circle was made of 39 foils with a spacing between foil centers of 1.25 cm. This distance was chosen because it gave a foil density that was high enough to give sufficient resolution but not so high that the time required to count all of the foils was unreasonable. Prior to placing the foils in the holder each one was massed so that the number of gold atoms would be known. The foils were run for a period of 180 minutes and were counted on a broad energy gamma spectroscope the next day for 5 minutes each. The time of 180 minutes was selected to give an activity of ~1000 Bq at the time the radiation ended. The counting time of 5 minutes was selected so that the number of counts would be above 2000 giving a counting error less than 2.2%**.** This experiment gave a benchmark beam fluence that would be compared to the post-tuning beam to determine the success of the tuning process.

The next step in optimizing the beam fluence was to tune the beam. The process of tuning the beam was to alter the distance between electrodes controlling the electric field acting on the plasma. The stability of this plasma is important as it is accelerated toward the target creating neutrons. By altering this electric field the team was able to increase the fluence of neutrons.

Once the beam was tuned a second experiment was conducted similar to the first to determine the fluence and profile of the neutron beam. An approximation of a circle of radius 7.5 was placed in the same location as the pre-tuning circle. The foils were irradiated for a period of 180 minutes and counted the next day for 5 minutes. The experiment was conducted in the same way so that the effect of tuning on the beam profile and fluence could be easily determined. Once this experiment was complete and the team was satisfied with the tuning of the beam the fluence with backscatter had to be determined to compare that with the manufacturer's quoted fluence of $1\text{-}2 * 10^7$ n/cm^2/s.

The final step in the experiment to characterize the neutron beam was to backscatter the neutrons to achieve the maximum possible fluence. While not useful to neutron imaging that would be done later with this machine this test had to be done to compare the tuned beam fluence to the manufacturer quoted fluence with backscatter. The backscattering was achieved by placing 5 cm of a polyethylene based plastic behind the foils. This would cause the neutrons to pass through the foils multiple times and would thus increase the measured fluence. The polyethylene thickness was chosen because it was the same as was used by the manufacturer.

It was with this set of 4 irradiations that the team hoped to optimize and characterize the beam flux and be able to compare it to the flux given by the manufacturer.

Theramization Measurements

This project team also wanted to demonstrate the thermalizing effects of polyethylene on fast neutrons. This was done by placing varying thicknesses of polyethylene between the foils and unmoderated neutrons emitted by the generator. The hydrogen atoms in the polyethylene would scatter the neutrons reducing their energy from 2.5MeV to ~.025eV

The neutrons that are in the main beam of the generator are thermalized by a built in moderator so to get unmoderated neutrons the side shielding of the generator had to be removed. Conducting the experiments on the side of the generator was undesirable as the fluence of neutrons is much less than that in the main beam. However there was no other option available to the project team for getting unmoderated neutrons. The removal of shielding from the side of the generator enabled the team to conduct experiments utilizing unmoderated neutrons.

Once the shielding was removed a set of four foils was placed 70 cm from the center of the vacuum chamber perpendicular to the beam direction. Four separate trials were conducted with 0, 1.25, 2.5, and 5 cm of polyethylene moderator between the generator and the foils. For each thickness the foils were irradiated for 90 minutes and counted for 60 minutes. The counting time of 60 minutes was chosen so that a sufficient number of counts could be obtained to reduce counting error below 4%.

These experiments enabled the team to characterize and optimized the beam flux and to observe the thermalizing effects of polyethylene.

Error Calculation

Throughout the process of the calculations the error propagation was important for the team to keep track of. The calculation that was used for this can be seen in Eq 9. In this equation σ_φ is the error in the neutron fluence. To find the error three parameters are required σ_A which is the error in activity, σ_n which is the error in the number of gold atoms, and σ_σ which is the error in the neutron cross section of ^{198}Au.

$$\sigma_\varphi^2 = (\frac{\partial\varphi}{\partial A(t)})^2\sigma_A^2 + (\frac{\partial\varphi}{\partial n})^2\sigma_n^2 + (\frac{\partial\varphi}{\partial\sigma})^2\sigma_\sigma^2 \qquad \text{Eq. 9}$$

σ_A was found by taking the square root of the number of counts from the gamma spectroscope, σ_n was calculated by taking the smalles value the scale would read to and finding the number of gold atoms that corresponded to, and σ_σ was given by the source for the cross section of gold. With this equation the team was able to translate the error in measurements that were made into error in neutron fluence.

Results

This series of experiments successfully found and optimized the fluence of the neutron beam from the generator that WPI recently received. The tuning successfully increased the beam fluence and the peak fluence was within the manufacturer expected value.

Fluence Optimization and Characterization

The results from the pre-tuning test can be seen in Figure 1**.** This yielded a maximum fluence of $3.7*10^6 \pm 2.6*10^4$ n/cm^2/s. As can be seen a dead spot was found in the middle of the beam which corresponds to a single gold foil.

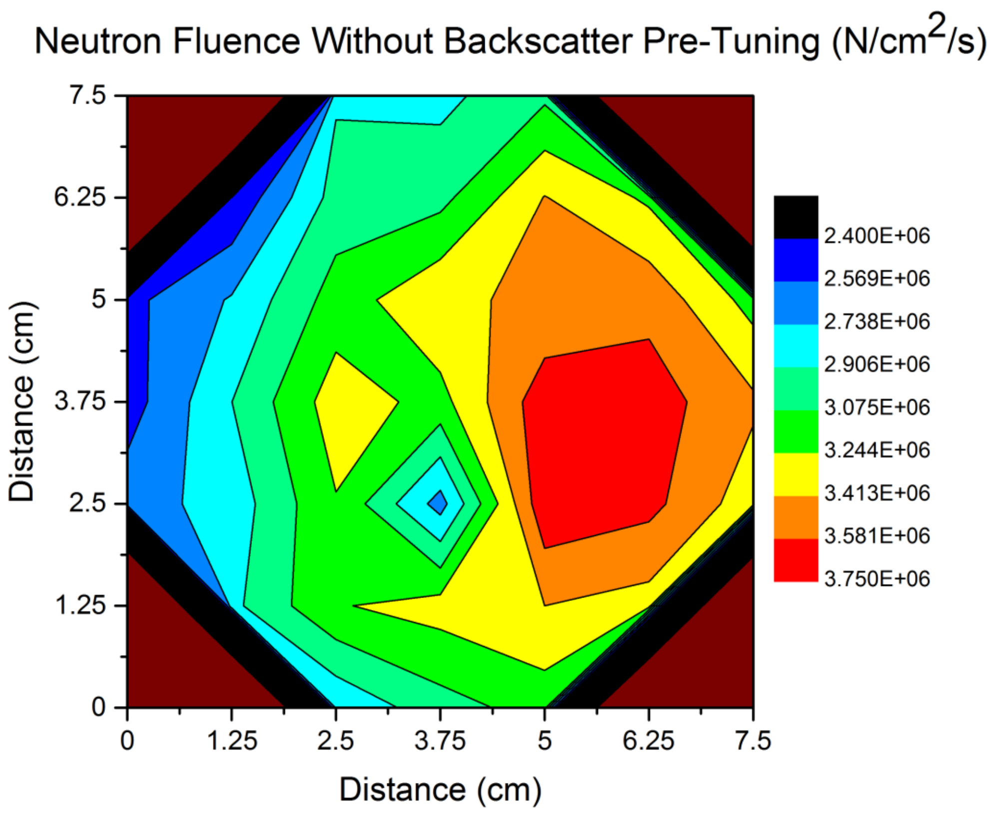

Figure 1: Fluence on the surface of the neutron generator before tuning

Once the project team had measured the fluence of the beam without tuning the beam could be tuned to optimize fluence. The factory tuning of the beam was found to be close to optimal so only small changes in the distances between the electrodes that produced the most stable plasma. The results of the fluence experiment after the beam had been tuned can be seen in Figure 2. The peak fluence increased by 8.7% to $4.02*10^6 \pm 3.5*10^4$ n/cm^2/s. The tuning process also shifted the beam spot to the left 3 cm which was a possible outcome of the tuning as the angle that the plasma strikes the target could have been altered. As in the previous measurement an area of low fluence can be observed in the center of the beam however with this measurement the low spot corresponded to 4 foils.

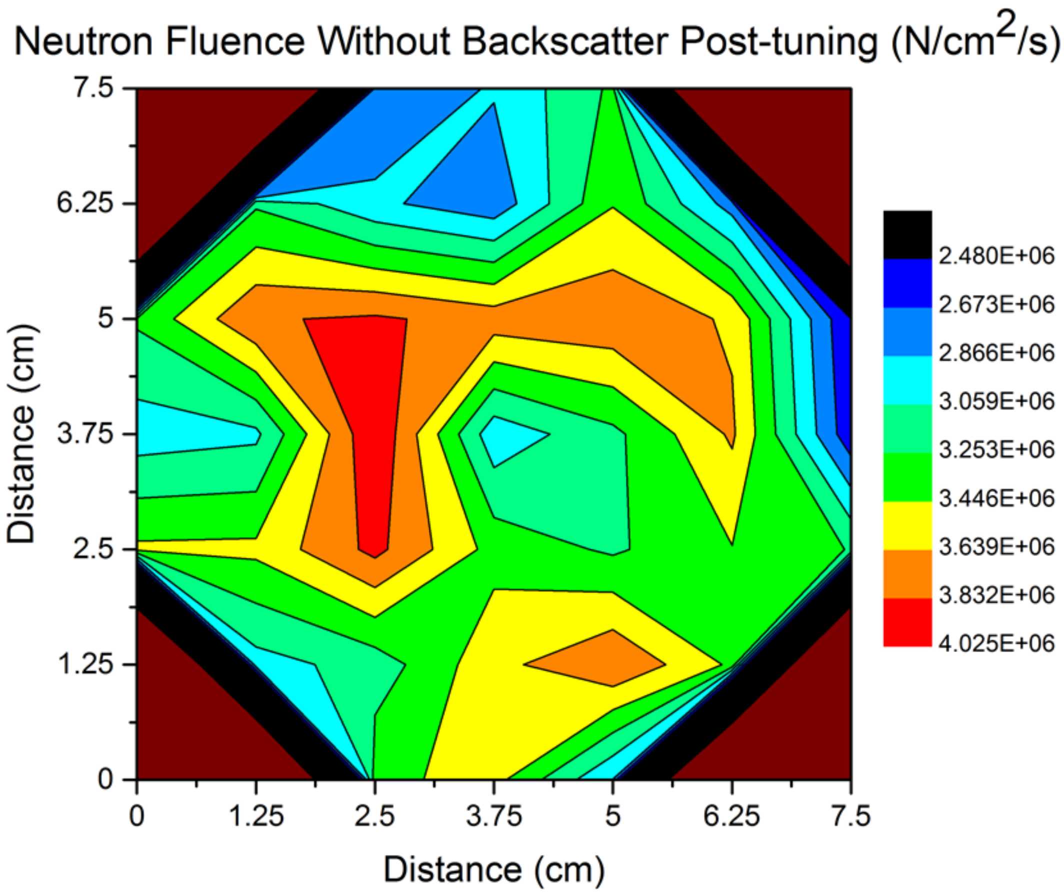

Figure 2: Fluence on the surface of the neutron generator after tuning

As the previous two measurements had shown an area of low fluence in the middle of the beam the team devised a trial that would determine if the area actually had a lower fluence or if it was caused by impurities in the foils. To do this the team placed a film in the beam spot that would darken when it interacted with gamma rays emitted by the neutron's interactions with the moderator on the generator.

While this measurement would not yield a fluence it would give the shape of the beam which would indicate whether or not there was a low spot in the middle.

The film was scanned and the beam profile can be seen in Figure 3**.** As can be seen there is no low area in the middle so the team concluded that the low spots were due to impurities in the gold foils or the foils becoming skewed in their holder. Both of these could significantly reduce the activity of the foil thus reducing the calculated fluence. Although the team could do nothing about foil purity steps were taken to assure that the foils remained perpendicular to the beam of the generator in future trials.

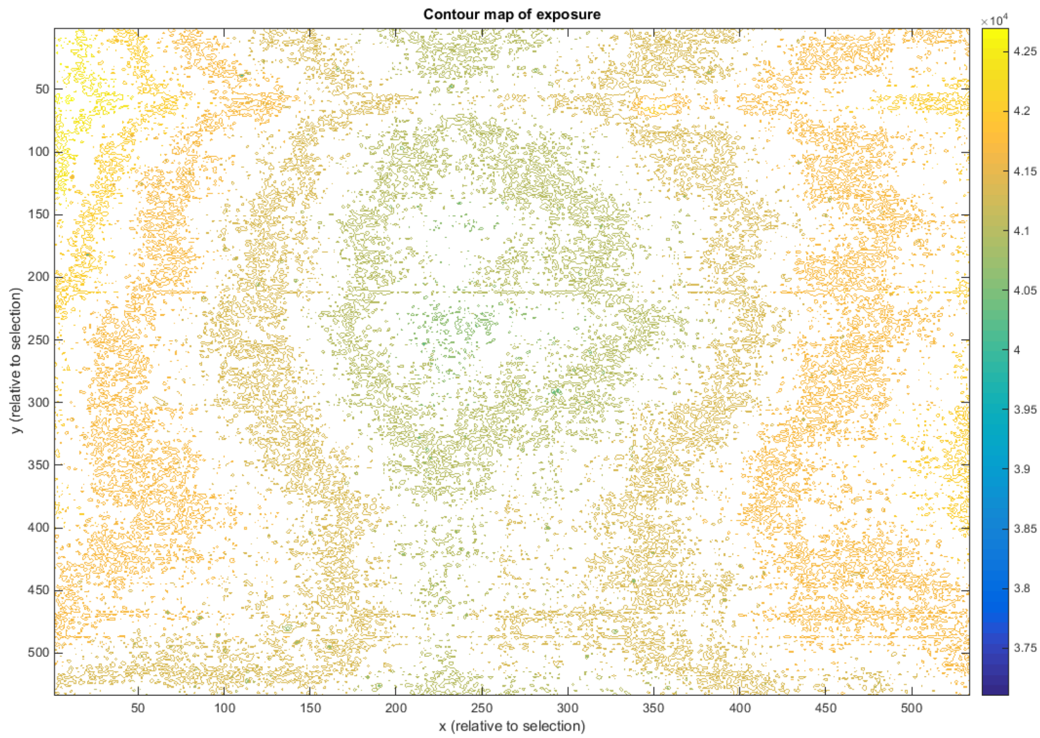

Figure 3: Gafchromic film placed on beam spot

The final step in determining the beam fluence was to backscatter the neutrons so that the fluence from our tuning could be compared to the fluence reported by the manufacturer. When 5 cm of polyethylene was applied to the back of the foils the activity increased dramatically. The peak measured fluence was $1.61*10^7 \pm 1.0*10^5$ n/cm^2/s which is approximately 4x the calculated peak fluence of the beam without back-scatter as can be seen in Figure 4. This was expected as the neutrons would be making multiple passes through the gold increasing the probability that they become absorbed by the nuclei. It was also noted that no area of low fluence was found in the middle of the beam confirming that the previous low readings had been an issue with the foils. The value that the team calculated for the fluence with backscatter was within the manufacturer expected fluence of 1-2*10^7 n/cm^2/s.

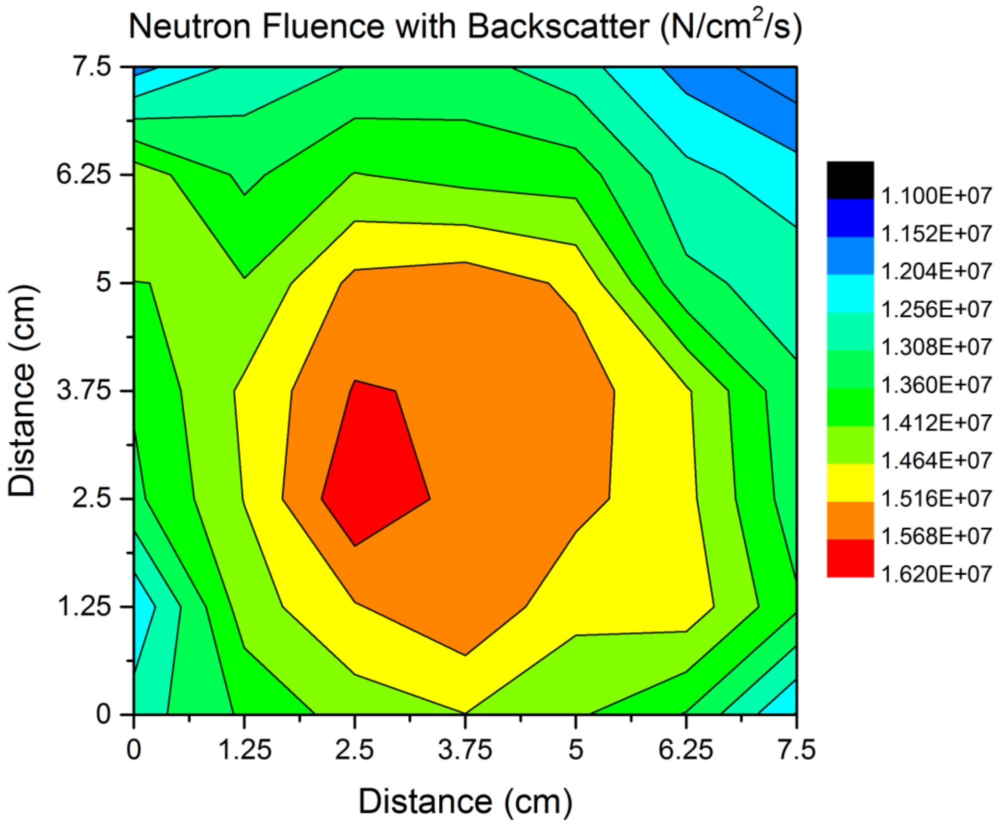

Figure 4: Fluence on the surface of the neutron generator after tuning with 5cm of polyethylene backscatterer

Theramization Measurements

The team conducted a second set of experiments to observe the effects of polyethylene as a moderating material on fast neutrons. As can be seen in Figure 5 the fluence increased linearly with the thickness of polyethylene. This was due to the increase in thermal neutrons that the polyethylene produced.

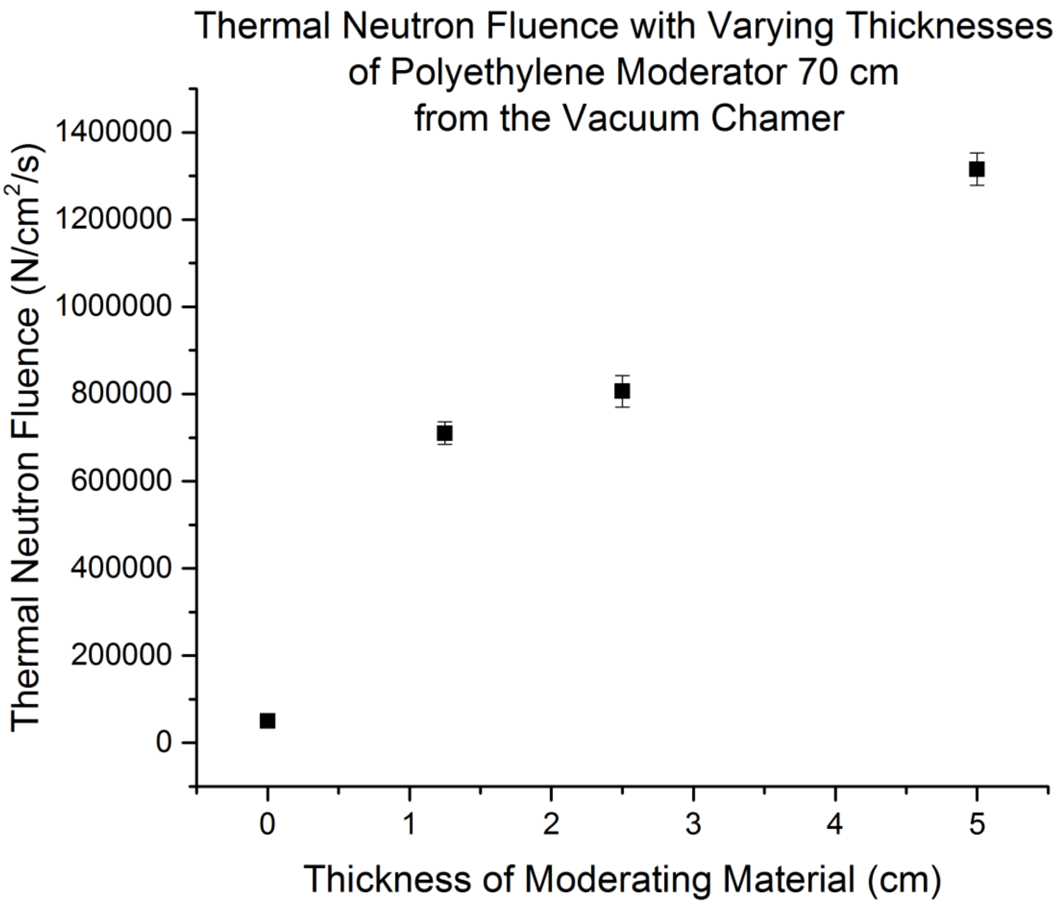

Figure 5: Thermal neutron fluence 70cm from the vacuum chamber

Conclusions

This project successfully optimized the beam of WPI's new deuterium-deuterium neutron generator. The peak flux was increased from $3.71*10^6$ to $4.02*10^6$ through careful tuning of the beam. The project was also successful at characterizing the fluence of the beam finding the flux within a 3.5cm radius of the peak fluence. The project team was also successful in observing the thermalizing effects of a polyethylene on fast neutrons. The team was satisfied with these results which will be of great use to the radiation lab at WPI.

Future Work

This project was successful in characterizing the thermal neutron fluence at the surface of the generator however the fluence farther from the surface of the generator was not measured. Future projects will look at the fluence at different distances from the surface generator. Knowing the fluence at different distances from the generator will be beneficial as the work that will be done with neutron imaging will not be done at the surface of the generator. The team would also have liked to cool the room that the neutron generator was in as some of the components in the generator become less stable at higher temperatures. During experimentation the room was ~32°C and if this could be reduced to ~20°C the stability of the beam could be increased. With these future measurements and changes the neutron generator will become much more useful for research into medical imaging.

References

Adani, N. and B. G. Fallone Neutron imaging using medical linacs.

Carter, R. S., et al. (1953). "Thermal Neutron Absorption Cross Sections of Boron and Gold." Physical Review 92(3): 716-721.

International Atomic Energy Agency, P. and A. International Atomic Energy (2008). Neutron Imaging: A non-destructive tool for materials testing, report of a coordinated research Project 2003-2006. Lanham, International Atomic Energy Agency.

Knoll, G. F. (1979). Radiation detection and measurement. New York, Wiley.

Lou, T. P. and C. SciTech (2003). Compact D-D/D-T neutron generators and their applications, United States. Dept. of Energy. Office of Science

Medich, D. C., et al. (2014). "Feasibility of Small Animal Anatomical and Functional Imaging with Neutrons: A Monte Carlo Simulation Study." IEEE Transactions on Nuclear Science 61(5): 2480-2488.

Nelkin, M., et al. (1960). Neutron thermalization in water.

Patrick, B. (1999). Neutron activation. Cleveland, Advanstar Communications, Inc. 23: 82.

Poole, M. J. (1966). "Neutron Thermalization." Nature 212(5061): 453-453.

SciTech, C. (1980). Low-neutron-fluence fusion-blanket dosimetry experiment, Idaho National Engineering Laboratory

SciTech, C. (1983). Neutron activation in EBT-P, distributed by the Office of Scientific and Technical Information, U.S. Dept. of Energy.

SciTech, C. (1988). High-fluence fusion neutron source, Lawrence Livermore National Laboratory

SciTech, C. (2004). Downscattered Neutron Imaging, United States. Dept. of Energy

SciTech, C. (2004). THERMAL NEUTRON BACKSCATTER IMAGING, Brookhaven National Laboratory

SciTech, C. (2006). Fast Neutron Imaging Systems, United States. Dept. of Energy

SciTech, C. (2008). High Intensity, Pulsed, D-D Neutron Generator, Lawrence Berkeley National Laboratory

Zobel, W. (1963). Experimental determination of corrections to the neutron activation of gold foils exposed in water. United States