Comparative Analysis of PVT Scintillators for the Development of a Fast Neutron Imager

THESIS

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By

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Abstract

The objective of this research is to conduct a comparative analysis of polyvinyltoluene (PVT) organic scintillators in order to aid Lawrence Livermore National Laboratory in the design of a PVT scintillator for fast neutron imaging. To achieve this goal, a neutron imaging apparatus has been developed to conduct neutron radiography using a neutron beam facility at The Ohio State University Research Reactor (OSURR). The neutron imaging apparatus is based on a low-cost single mirror reflection configuration that consists of a neutron sensitive scintillator, a light tight box, a mirror, and a cooled charge-coupled device (CCD) camera. The light tight box was designed, machined, and built in-house specifically to fit into the space available at the neutron beam facility. The camera position is adjustable within the box in order to provide an adjustable field of view, which allows the object or region of interest to take full advantage of the CCD chip size. The spatial resolution of the scintillator was characterized by using Modulation Transfer Function (MTF) and an optical test target. The light yield was measured by the summation of pixel values in the same region of interest in each scintillator. Maximum resolution for a lithium loaded PVT (1.3% by weight) scintillator with thickness of 2.2 mm was 10.9 lp/mm for thermal neutrons. The resolution decreased by 11% with an increase of 1.1 mm in thickness. For fast neutrons with an average energy of 2 MeV, Li-loading increased the light yield of PVT by 29%.
For 2.45 MeV neutrons produced by a D-D neutron generator, PVT with a Europium fluor produced 2.7 ± 0.2 times more light than a standard PVT scintillator. The combination of lithium loading with a Eu fluor in PVT produces an efficient dual-purpose fast and thermal neutron imager, as anticipated.
Dedication

I dedicate this research to my Lord and Savior Jesus Christ and my family. Lord, thank you for giving me Your work to do. Susan, my beautiful wife, I want to thank you for being my helper in all things in this life. Elwood and Ezra, my two sons, I look forward to the day when I can explain and show you what I did during your first years of life.

“It is the glory of God to conceal a matter, but the glory of kings is to search out a matter.” Proverbs 25:2

“Whatever you do, do your work heartily, as for the Lord rather than for men.”

Colossians 3:23
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Lastly, I am thankful to the nuclear engineering professors Dr. Blue, Dr. Aldemir, Dr. Zhang, and Dr. Sun who taught me the necessary skills required for my next assignment as a nuclear engineering professor at the United States Military Academy.
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Major Field: Nuclear Engineering
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Chapter 1: Neutrons and Their Interactions with Matter

Neutrons are electrically neutral and interact directly with the nucleus of atoms, which allows them to deeply penetrate materials except for a few isotopes with high neutron absorbing cross-sections. Although free neutrons decay with a half-life of about 10.6 minutes, they would be absorbed in the materials long before they could undergo $\beta^-$ decay (Christensen, 1972). Neutrons are in existence at an extremely low natural background level of roughly $0.01 \text{ cm}^{-2}\text{s}^{-1}$ at sea level (Florek, 1996). The artificial neutron sources includes radioisotopes, spallation reaction (Lisowski, 1990), fusion reactions (Brysk, 1973), ($\gamma$, n) reactions, and most abundantly, in nuclear reactors.

Neutrons have many reaction channels through their interactions with nuclei, but radiative capture, charged-particle productions, and elastic scattering are those most pertinent to this research. The probability of these interactions depends on the target nucleus and the energy of the incident neutron. In this research, a neutron is described as either slow or fast. A slow neutron has energy below 0.55 eV, the effective cadmium cutoff energy for 1 mm thickness of cadmium, and a fast neutron’s energy is above 0.55 eV (ASTM E261-10, 2010). The fast neutron energy spectrum is peaked at 0.73 MeV and has mean energy of ~2 MeV, due to the thermal fission spectrum of the nuclear reactor facility used in this study (Lamarsh, 2001).
Elastic scattering is the process where a neutron collides with a nucleus, transferring a portion of its kinetic energy to the nucleus that remains at its ground state. The kinetic energy transferred to a nucleus by a slow neutron during elastic scattering is insignificant, although the interaction is probable. For fast neutrons, the kinetic energy transferred during an elastic scattering event can be significant and results in a recoil nucleus. Multiple scattering events enable a neutron to slow down, lose energy, and reach thermal equilibrium with the atoms in the surrounding material, thus becoming a thermal neutron. Thermal neutrons have an average energy of 0.025 eV if the scattering medium is at room temperature. The recoil nucleus behaves much like a charged particle as it slows down, ionizing and exciting electrons along its path. The amount of energy transferred to a recoil nucleus can be calculated from the following equation, where $E_R$ is the recoil nucleus energy, $A$ is the atomic number of the recoil nucleus, $\theta$ is the scattering angle of the recoil nucleus, and $E_n$ is the energy of the incident neutron (Allen, 1960).

$$E_R = \frac{4A}{(1 + A)^2}cos^2(\theta)E_n$$

From the equation above, it can be seen a recoil nucleus’ energy is dependent on its scattering angle. In the case of hydrogen, the proton nucleus is nearly the same mass as the neutron, and in a head on collision ($\theta = 0$) the neutron transfers all of its energy to the proton, creating a recoiled proton. Due to their nearly equal mass, the probability of a recoil proton having any energy up to the maximum energy of the incident neutron is constant for neutron energies below 10 MeV. Thus, the average energy of a recoil proton undergoing a neutron scattering event is $0.5E_n$.  

2
Neutron interaction probabilities with specific nuclei are expressed as microscopic cross-sections ($\sigma_i$) with barns as the unit (1 barn = $10^{-24}$ cm$^2$). The macroscopic cross-section ($\Sigma_i$) is the atom density of the material the neutrons will be interacting with multiplied by the microscopic cross-section and has a unit of cm$^{-1}$. The mean free path of a neutron is the average distance a neutron will travel in a material before it undergoes an interaction with a nucleus and is simply found by the reciprocal of the macroscopic cross-section.

$$\text{mean free path} = 1/\Sigma_i$$

(2)

To calculate the number of neutron interactions per unit volume per second in a material, i.e., the collision density ($F$), the neutron flux ($\phi$) is multiplied by the macroscopic cross-section of a particular interaction (Lamarsh, 2001).

$$F = \phi \Sigma_i$$

(3)

The uncollided intensity of neutrons ($I$) passing through a material of a certain thickness ($x$) with an incident neutron intensity ($I_0$) can be found by an exponential attenuation law as a function of the macroscopic cross-section.
The attenuation and transmission of neutrons through a material provides the basis for the most utilized neutron radiography technique, the one based on shadow-projection (Heller, 2009).

Charged particle reactions occur when a nucleus absorbs a neutron and divides into charged particles. These reactions are also most probable with slow and thermal neutrons, following $1/v$ rule. In this research the $^{6}\text{Li} \ (n,\alpha)\ ^{3}\text{H}$ reaction is of primary concern. This reaction releases two charged particles in opposite directions, an alpha (2.05 MeV) and a triton (2.73 MeV), for a total energy 4.78 MeV. Table 1 summarizes other reactions frequently used for neutron detection (Crow, 2009).

Table 1: Thermal Neutron Detection Reactions

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Reaction</th>
<th>$\sigma_a$ (barns) at 0.025 eV</th>
<th>Charged Particles and Energies (keV)</th>
<th>$\gamma$-ray Production?</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\text{He}$</td>
<td>$^3\text{He}(n,p)\ ^3\text{H}$</td>
<td>5,333</td>
<td>$p$: 573 $^3\text{H}$: 191</td>
<td>No</td>
</tr>
<tr>
<td>$^6\text{Li}$</td>
<td>$^6\text{Li} \ (n,\alpha)\ ^3\text{H}$</td>
<td>940</td>
<td>$^3\text{H}$: 2,727 $\alpha$: 2,055</td>
<td>No</td>
</tr>
<tr>
<td>$^{10}\text{B}$</td>
<td>$^{10}\text{B}(n, \alpha)\ ^7\text{Li}$</td>
<td>3,835</td>
<td>$\alpha$: 1,472 $^7\text{Li}$: 480</td>
<td>Yes</td>
</tr>
<tr>
<td>nat $\text{Cd}$</td>
<td>nat $\text{Cd}(n, \gamma)$</td>
<td>2,463</td>
<td>-</td>
<td>Yes</td>
</tr>
<tr>
<td>$^{113}\text{Cd}$</td>
<td>$^{113}\text{Cd}(n, \gamma)$</td>
<td>19,964</td>
<td>-</td>
<td>Yes</td>
</tr>
<tr>
<td>nat $\text{Gd}$</td>
<td>nat $\text{Gd}(n,\gamma)$</td>
<td>49,700</td>
<td>Conversion electron: 29-191</td>
<td>Yes</td>
</tr>
<tr>
<td>$^{157}\text{Gd}$</td>
<td>$^{157}\text{Gd}(n,\gamma)\ ^{158}\text{Gd}$</td>
<td>259,000</td>
<td>Conversion electron: 29-182</td>
<td>Yes</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>$^{235}\text{U}(n,f)$</td>
<td>681</td>
<td>Fission products</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Radiative capture is when a neutron is absorbed by a nucleus and one or more gamma rays are emitted. These gamma rays are called prompt gammas. These reactions are often known as $(n, \gamma)$ reactions and most often occur with thermal neutrons. Cadmium is an example of a material that could be used for neutron detection and imaging by way of radiative capture. Neutron activation is the term used to describe a radioactive isotope formed through neutron absorption. Radiative capture often competes with charged particle reactions.

In general, the probabilities of neutron absorption interactions are inversely proportional to the incident neutron energy, although some threshold energy absorption reactions become possible. Table 2 lists all the possible $^6\text{Li}$ reactions with fast neutrons.

**Table 2: $^6\text{Li}$ Reaction Channel with Neutrons**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sigma$ @ 1 MeV (barns)</th>
<th>$\sigma$ @ 2.45 MeV (barns)</th>
<th>$\sigma$ @ 14 MeV (barns)</th>
<th>Threshold (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic</td>
<td>1.011</td>
<td>1.276</td>
<td>0.863</td>
<td>0</td>
</tr>
<tr>
<td>Inelastic</td>
<td>0.000</td>
<td>0.059</td>
<td>0.477</td>
<td>1.75</td>
</tr>
<tr>
<td>n,2n+a</td>
<td>0.000</td>
<td>0.000</td>
<td>0.078</td>
<td>4.32</td>
</tr>
<tr>
<td>n,α</td>
<td>0.239</td>
<td>0.206</td>
<td>0.026</td>
<td>0</td>
</tr>
<tr>
<td>n,p</td>
<td>0.000</td>
<td>0.000</td>
<td>0.006</td>
<td>3.18</td>
</tr>
<tr>
<td>n,γ</td>
<td>$1.16 \times 10^{-05}$</td>
<td>$1.11 \times 10^{-05}$</td>
<td>$1.02 \times 10^{-05}$</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>1.250</td>
<td>1.542</td>
<td>1.450</td>
<td>0</td>
</tr>
</tbody>
</table>
Chapter 2: Neutron Radiography

Neutron imaging is the production of images by transmitted neutrons from a beam through an object and onto a detector. Neutron imaging, or neutron radiography, is essentially performed the same way as medical X-rays, although they interact with matter in different ways. X-rays interact with electrons; therefore, high Z elements have dense electron clouds and attenuate X-rays more than low Z elements. Neutrons interact with nuclei and in general, hydrogen attenuates neutrons more due to scattering while lithium, boron, gadolinium, and cadmium etc. attenuate neutrons through absorption. Therefore, X-ray imaging and neutron imaging are complementary (Heller, 2009). Although neutron imaging is more expensive in terms of source availability, harder to produce high signal-to-noise ratio due to low flux of neutron source, and more complicated than x-ray imaging, it has a variety of qualities that make it well-suited for certain imaging applications. Neutrons deeply penetrate most materials, which allow neutrons to image very large objects nondestructively. Neutrons also provide good contrast for objects containing light atom structures surrounded by heavy atom structures. Isotopes of an element have different neutron scattering and absorption cross-sections. Therefore, a greater cross-section isotope can replace a lower cross-section isotope without changing the chemical composition of a material. This will increase the desire neutron interaction and enhance the image (Anderson, 2009).
Neutrons are detected because of their interactions with nuclei. Fast neutrons collide with nuclei and produce recoil nuclei that ionize the material around them. Slow neutrons produce ionization through charged particle reactions as previously discussed. Nuclei that have large neutron capture cross-sections and produce charged particles are known as neutron converters.

There are several neutron imaging techniques which include the use of a collimated neutron beam for shadow imaging (Satija, 2003), use of pin-hole imaging (Morgan, 2001) or coded mask (Zou, 2011) for uncollimated neutron beams, phase contrast radiography (Kardjilov, 2004), and the possible double scattering for fast neutron imaging (Herzo, 1975). Transmitted neutron radiography, or shadow imaging, is most commonly used and is also applied in this study to evaluate the Li-loaded PVT, mainly due to the availability of a collimated neutron beam facility at the OSURR. Shadow imaging relies on transmitted neutrons to produce recoil nuclei or charged particles produced from neutron converters to ionize and excite electrons in a scintillator to produce light, which can be captured with a CCD camera forming a shadow image.

The basic set-up of a neutron imaging apparatus for shadow imaging is a light tight box, a scintillator screen, a 45-degree front surface mirror, a lens, and typically a cooled CCD camera (Crow, 2009). There are important considerations with each aspect of this neutron imaging system. A tradeoff exists between the scintillator thickness and spatial resolution. Neutron interaction efficiency is gained with a thicker scintillator and it increases light yield, but it results in degradation in spatial resolution. A front surface mirror eliminates multiple reflection effects. The mirror positioned at a 45 degree angle
enables the camera to be outside the beam, protecting it from radiation which can damage the camera sensor. Depending on the strength of the neutron beam, the exposure time may need to be very long to capture enough light. Longer exposure time generates additional heat which produces dark current on the CCD sensor, which requires it to be cooled. At the time of Anderson’s publication in 2009, a cooled CCD camera neutron imaging system had achieved 50 micron resolution, which began to approach the theoretical resolution of a scintillation screen. Currently, the CCD camera imaging system is the primary detection technique for most imaging facilities due to its fast acquisition time and flexibility (Crow, 2009).
Chapter 3: Organic Scintillators

Scintillators are materials that absorb ionizing radiation and emit low-energy photons (Herwig, 2009). Organic scintillators are composed of conjugated and aromatic organic molecules which have the inherent property of luminescence due to their electronic structure. Luminescence is the property of light emission with a characteristic spectrum, following the absorption of radiation. These organic molecules form molecular crystals bound by the Van der Waals forces and maintain their identity, electronic structure, and luminescence. Therefore, luminescence is possible when the organics are part of vapor, liquid, or solid solution or in a liquid, plastic, glassy, or crystalline state (Birks, 1964).

The electronic structure of the carbon atom primarily determines the structure of organic molecules. The ground state of Carbon is $1s^22s^22p^2$ and has four $2p$ valence electron orbitals. The carbon atom is “prepared for binding” when one of the electrons from the $2s$ state moves to the $2p$ state in order to form a compound. When the carbon atom is “prepared for binding,” the one $2s$ and the three $2p$ valence electron orbitals are mixed, or hybridized, in three different configurations (Birks, 1964).

When all four valence electron orbitals are hybridized, it is known as tetrahedral, or $sp^3$ hybridization. Compounds formed from this configuration like methane ($\text{CH}_4$) are saturated compounds and are not luminescent. Trigonal, or $sp^2$ hybridization, occurs
when one of the p orbitals is left unchanged. The bonds of the hybrid orbitals, which are symmetrical about the bonding axes and the plane of the molecule, are called \( \sigma \)-bonds and the electrons that occupy them are called \( \sigma \)-electrons. The p orbital, which is mirror symmetric about the nodal plane, is known as a \( \pi \)-electron. The simplest trigonal compound is ethylene, in which a double bond forms between the carbon atoms. The second bond is between the unchanged p orbitals of each carbon atom resulting in a \( \pi \)-bond. The excitation of \( \pi \)-electrons is responsible for the luminescence of organic molecules. Digonal or \( sp \) hybridization, is where two orbitals are left unchanged and two are hybridized. An example is acetylene, where the carbon atoms are triple bonded having two \( \pi \)-electrons. Acetylene is also luminescent (Birks, 1964). Thus, an organic scintillator must be rich in \( \pi \)-electrons.

By spin statistics, during the scintillation process, there are three triplet excited states created for every one singlet excited state (Rupert, 2012). A \( \pi \)-electron can be excited to multiple singlet (spin 0) states following energy absorption. The ground state of an electron is denoted \( S_{00} \) and the first energy state is denoted \( S_{10} \). As seen, the singlet states are designated with an S and a two digit number, where the first number is the excited state and the second is the vibrational state of the electron. The typical spacing of the vibrational states is 0.15 eV. For organic scintillators, the energy gap between \( S_{10} \) and \( S_{00} \) is between 3-4 eV, which corresponds to a blue or ultraviolet light. If an electron is excited to the \( S_2 \) or a higher energy state, the electron quickly \( (10^{11} \text{ s}) \) returns to the \( S_1 \) state without emitting radiation due to the internal conversion between adjacent energy states. This is fortunate because nearly all absorption results in a light emission. The light
emission is a spectrum, however, because of the vibration states of the ground state of the electron. Thus, fluorescence occurs when there is a radiative transition from $S_1$ to $S_0$, typically within $10^{-8}$ to $10^{-9}$ seconds following absorption (Birks, 1964). Fluorescence decays exponentially.

A small portion of electrons will undergo a radiationless transition from the $S_1$ energy state to the first triplet state $T_{10}$ (spin 1). This is often called intersystem crossing. The radiative transition from $T_{10}$ to $S_0$ results in a longer decay time ($10^{-4}$ s or longer) and a longer wavelength of light emission. This process is called phosphorescence (Birks, 1964). Triplet excitation is lost to radiationless decay, since the phosphorescence lifetimes are very slow in standard organic scintillators. This mechanism is responsible for the observed low light yield in traditional organic scintillators of only about 10,000 photons/MeV, compared to 40,000 photons/MeV and higher in typical inorganic scintillators.

The third and final mechanism for light emission from an organic molecule results from the excitation of a molecule in a $T_1$ state or another metastable state into the $S_1$ state. The radiative transition is the same of fluorescence, but with a long decay period ($10^{-6}$ s), which does not exponentially decay. This process is called delayed fluorescence (Birks, 1964).
The fluorescent energy from the $S_{10}$ to $S_{00}$ ground states is almost always less than the excitation energy. Therefore, fluorescence of organic scintillators is generally not self-absorbed by the scintillator, because there is very little overlap between the excitation energy spectrum and the light emission spectrum. As previously mentioned, organic scintillators often emit ultraviolet or blue light. A fluor is often added to an organic scintillator because many organics have too low of a scintillation to be of practical use (Birks, 1964). The fluor readily receives the energy from the excited singlet and/or triplet state of an organic molecule and emits light with a much greater efficiency and often at a lower wavelength than the host organic scintillator (Rupert, 2012).

Recently, it has been discovered that certain metal-organic fluors when employed in organic light emitting diodes (OLED’s), or in scintillators, can provide enhanced light yields due to the mixed singlet-triplet character of their lowest excited state, which arises
due to spin-orbit coupling from the high-Z metal in the molecule. Spin-orbit coupling fluors have emission efficiencies under ionizing radiation of 3-4 times that of traditional singlet fluors (Rupert, 2012). The best known of these spin-orbit coupling fluors are the Iridium complexes, widely used in OLED lighting. Other high light yield fluors containing high-Z metals include Pt, Tb, and Eu complexes.

Although self-absorption is often negligible, there is a significant percentage of scintillation light that is internally reflected at the scintillator-air interface (Birks, 1964). The percentage of light internally reflected ($r$) is determined by the refractive index ($\mu$) of a material, which is the ratio of the speed of light in a vacuum to the speed of light in the material (Rieke, 2003).

$$r = \frac{(\mu - 1)^2}{(\mu + 1)^2}$$

(5)

A scintillator with a refractive index of 1.5 will reflect 4% of the light normally incident to it. As the angle of incidence increases, the percentage of reflectance also increases.

The critical angle ($C$) at which 100% of the light is reflected is found from the following equation (Birks, 1964).

$$C = \sin^{-1}\left(\frac{1}{\mu}\right)$$

(6)
3.1: Scintillation Efficiency

The transfer of energy from incident radiation to electrons results in excitation and ionization of electrons. Both $\pi$-electrons and $\sigma$-electrons can be excited and ionized. As discussed, excited $\pi$-electrons primarily yield fluorescence. The recombination of ionized $\pi$-electrons primarily yields $\pi$-electrons in a triplet state contributing to delayed scintillation. The excitation of $\sigma$-electrons does not yield any light, and the energy is dissipated thermally. The ionization of $\sigma$-electrons causes temporary and permanent molecular damage to the scintillator. The energy of recombined $\sigma$-electrons is once again thermally dissipated. The permanent damage introduces quenching centers which degrade light yield under long term radiation exposure. The temporary molecular damage results in ionization quenching (Birks, 1964).

Scintillation efficiency ($S$) is the fraction of all incident particle energy that is converted into visible light. The scintillation efficiency is relatively small, approximately four percent, with most of the energy dissipated nonradiatively as heat (Birks, 1964). Approximately 10% of the scintillation efficiency results in delayed fluorescence. The scintillation efficiency is dependent upon type and energy of incident radiation. For particles that are heavier or slower than fast electrons, the scintillation efficiency is decreased. For instance, comparing electrons, protons, and alpha particles of 5 MeV for each case, the light yield ratio is 10:5:1, respectively (Birks, 1964). With this experimental observation, Birks related light yield of a scintillator to the specific energy loss, also known as linear stopping power, of a charged particle. The specific energy loss...
of charged particles describes the rate of energy lost by a charge particle per unit path
length \( (dE/dx) \) (Ziegler, 1985). As a particle loses energy, its specific energy loss
increases until the particle stops by elimination, as in the case of an electron or a charged
particle which accumulates enough electrons to become a neutral atom. A free electron
loses energy through exciting and ionizing the electrons of the material it passes through
or radiatively by bremsstrahlung. Heavy charged particles lose energy through excitation,
ionization, and collisions with nuclei. Heavy charged particles have greater mass and
charge than electrons, resulting in a greater specific energy loss. This makes their paths
much shorter and straighter in a material. Therefore, according to Birks’ assumption, a
heavier charged particle produces a high ionization density along its track, leading to
ionization quenching from damaged molecules and results in a decreased scintillation
efficiency. Birks formula relates the fluorescent energy \( (dL/dx) \) emitted per unit path
length and specific energy loss \( (dE/dx) \), in order to describe the response of organic
scintillators to charged particles.

\[
\frac{dL}{dx} = \frac{s \frac{dE}{dx}}{1 + k_B \frac{dE}{dx}} 
\]  

(7)

The factor \( k_B \) is essentially an adjustable parameter to fit experimental data. For
electrons, the specific energy loss is small and the equation simplifies to \( L = SE \). Upon
further investigation of a variety of organic scintillators, Chou derived an extended
version of Birks’ formula in order to fit experimental data more closely, where \( C \) is
treated as an empirically fit parameter (Chou, 1952).
\[
\frac{dL}{dx} = \frac{S \frac{dE}{dx}}{1 + kB \frac{dE}{dx} + C \left( \frac{dE}{dx} \right)^2}
\] 

Equation 8

Craun and Smith (1971) demonstrated the accuracy of Equations 7 and 8 by using them to fit their data from the response of several organic scintillators to charged particles. For protons up to 5 MeV in many organic scintillators, the light yield is proportional to \(E^{3/2}\) and then becomes approximately linear above 5 MeV (Knoll, 2010).

The term MeV electron equivalent (MeVee) is used to place light yield on an absolute basis (Knoll, 2010). One MeVee is equivalent to the light yield of a 1 MeV electron. Thus, it may require a proton of several MeV to produce 1 MeVee.

Most organic materials transfer excitation energy from molecule to molecule before de-excitation occurs. Therefore, a relatively small amount of an organic scintillator can be added to a solvent, an organic material, and the majority of the excitation energy will eventually find its way to a scintillator molecule where light can be emitted (Birks, 1964). This mixture of an organic scintillator and a solvent is referred to as a binary solution. A mixture of three constituents is considered a ternary solution. These solutions are found as plastics, liquids, and crystals, but with respect to this research, only plastic scintillators will be explored.
3.2: Polyvinyltoluene (PVT)

Polyvinyltoluene (PVT) is an organic plastic scintillator and is widely used commercially for plastic scintillator preparations (Birks, 1964). PVT contains a benzenic ring bonded to a methyl group and a vinylic group. The physical properties of PVT are described in the table below (Torrisi, 2002).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Formula</td>
<td>((C_9H_{10})_n)</td>
</tr>
<tr>
<td>Density (g/cm(^3))</td>
<td>1.032</td>
</tr>
<tr>
<td>Decay time of light (ns)</td>
<td>2.5</td>
</tr>
<tr>
<td>Max light emission (nm)</td>
<td>423</td>
</tr>
<tr>
<td>Index of Refraction</td>
<td>1.58</td>
</tr>
</tbody>
</table>

The approximate light yield of typical PVT scintillators is 10,000 photons/MeV when exposed to electrons. Compared to sodium iodide (NaI), a standard inorganic scintillator which yields 38,000 photons/MeV, this light yield is small. Although the light yield is small, PVT has the advantages of a fast decay time, cheap to produce, durable, and can be formed into almost any size and shape. Furthermore, PVT is ideal for fast neutron imaging because of its high hydrogen content. The recoil protons can excite \(\pi\)-electrons along its path that lead to fluorescence. Another advantage of plastic scintillators like PVT for fast neutron detection is their response is non-directional,
because the emission of light along the excitation and ionization path of charged particles is isotropic.
Chapter 4: CCD Cameras and Photography

There are three major aspects critical to the optical path between the scintillation screen and the camera: a light proof box, a lens to focus light, and the focal plane which records the light focused from the lens (Long, 2010). For scientific imaging, all three of these aspects are important to consider. The light proof box and the actual size of the camera are more a consideration of available space for the camera in an imaging application than functionality. In terms of lenses, there are several types to choose from, including zoom, fixed focal length, telephoto, and macro lenses. A lens is crucial to the image quality, especially the resolution. The focal plane of a digital camera is the image sensor. Primarily, there are three types of image sensors: the charge coupled device (CCD), complementary metal oxide semiconductor (CMOS), and charge injection device (CID). The CCD image sensor technology is ubiquitously used in modern daily lives and is the most mature. The CMOS sensors are nearly comparable to CCD sensors (Durin, 2014).

A complete discussion of digital cameras and digital photography is beyond the scope of this research. Only those concepts pertinent to this research will be addressed. In this research, a cooled CCD camera with a 25 mm fixed focal length lens was used.
4.1: Charged Coupled Device (CCD)

Willard Boyle and George Smith invented the charge-coupled device (CCD) on October 19, 1969 while working at Bell Telephone Laboratories. The CCD was originally developed as a memory device, though it quickly flourished in imaging applications. The CCD image sensor is essentially a silicon semiconductor that has been divided into a two dimensional array of pixels. Each pixel acts as a photodiode, where light photons are absorbed in the silicon by the photoelectric effect creating electron hole pairs. The electrons accumulate in each pixel throughout the exposure time, after which the charges are transferred vertically and horizontally from pixel to pixel until each pixel has been read out and saved as an image file. The Analog to Digital Unit (ADU) is the number assigned to a pixel in an image file, which is proportional to the collected charge in that pixel. The gain of the analog to digital converter determines how many electrons or amount of charge is equal to one ADU. Therefore, units of gain are e^-/ADU (Howell, 2006). Review Janesick (2001) and Durin (2014) to gain a thorough understanding of CCDs.

The quantum efficiency (QE) of a CCD image sensor is the ratio of incident photons that create electron hole pairs to the total number of incident photons to the photosite, the light sensitive portion of the pixel. It is important to distinguish between the photosite area and the pixel area. Pixels have a fill factor, which is the pixel area in percent that is sensitive to light. Depending on the method of charge transfer, the pixel
size, and the electronic mountings, the fill factor can vary greatly. An interline transfer CCD has shield strips which block light and decrease the fill factor. Thus, manufacturers place a micro lens on each pixel to direct more light to the photosite to increase the effective size of the pixel (Jacobson, 2000).

4.2: Imaging System Parameters

There are five important parameters to understand when it comes to digital photography and advanced photography concepts:

- **Field of View (FOV):** The horizontal and vertical dimension of an object imaged by the cameras sensor.
- **Working Distance (WD):** The distance between the front of the lens and the object being imaged.
- **Resolution:** The minimum feature size that can be distinguish by a camera.
- **Depth of Field (DOF):** The range of movement forward and backward the object can have without refocusing the lens.
- **Sensor Size:** The size of a camera’s active area, typically specified in the horizontal dimension. This is found by multiplying the number of active pixels in the horizontal dimension by the pixel width.

Another important parameter is the Primary Magnification (PMAG). It is the ratio between sensor size and FOV. These parameters are all linked to two aspects of the imaging system: the lens and the imaging sensor size (Imaging Resource Guide, 2014).
A fixed focal length lens has a fixed angular field of view (AFOV). A fixed focal length lens is measured by the distance travelled by the projected image from the principle rear plane of the lens to the image sensor. This distance determines a fixed AFOV for the lens. As previously mentioned, a 25 mm fixed focal length lens was used in this research. Therefore, the distance between the back of the lens to image sensor is 25 mm. The AFOV is generally determined by the horizontal dimension of the image sensor. Therefore, using simple trigonometry, the approximate AFOV can be determined.

\[
AFOV (°) = 2 \times \arctan \left( \frac{\text{sensor horizontal length (mm)}}{2 \times \text{focal length (mm)}} \right) \tag{9}
\]

The determination of the AFOV leads to the calculation of the FOV. This can be determined by the following formula.

\[
\text{Horizontal FOV (mm)} = 2 \times WD \times \tan \left( \frac{AFOV (°)}{2} \right) \tag{10}
\]

Figure 3: FOV of a fixed focal length lens
The FOV can only be changed with a fixed focal length lens by either moving closer to or farther from the object, effectively changing the working distance. Depending on the working distance, each pixel will represent a fixed area of the object imaged. Therefore, the determination of the field of view is essential because it enables a pixel calibration to be determined (Imaging Resource Guide, 2014).

The FOV being measured in horizontal is a matter of preference. The same calculations can be determined with vertical dimensions. Every image sensor, however, has an aspect ratio: the ratio of its horizontal dimension to its vertical dimension. Therefore, the vertical FOV can be found by dividing the horizontal FOV by the aspect ratio.

4.3: Resolution

The resolution of an imaging system is complex. There are a variety of factors involved, from contrast to light collection efficiency, which is defined by the quality and type of lens, aperture, working distance, and pixel size. The resolution calculation begins with pixel size, because the smallest detail that can be resolved is limited by the pixel size. Resolution is often discussed in terms of a frequency measured in line pairs per mm (lp/mm). A line pair consists of an adjacent black and white line. Therefore, the highest frequency of line pairs that can be resolved by a sensor, its Nyquist frequency, is two pixels. If a line pair is smaller than the width of two pixels, the pixels cannot resolve the line pair, because the division of the line pair would be in the middle of a pixel. Thus
each pixel would be gray as opposed to black (no light) to white (light). Therefore, the sensor resolution, also called the image space resolution, can be determined by the following equation.

\[
\text{image space resolution } \left( \frac{\text{lp}}{\text{mm}} \right) = \frac{1000 \left( \frac{\text{lp}}{\text{mm}} \right)}{2 \times \text{pixel size (um)}} \tag{11}
\]

In order to find the spatial resolution, or object space resolution, of the imaging system the PMAG is determined.

\[
PMAG = \frac{\text{horizontal sensor size (mm)}}{\text{FOV (mm)}} \tag{12}
\]

It is important to note that the PMAG changes with the working distance, because the FOV changes. Thus, the further a camera is from an object, the smaller the PMAG, and therefore, each pixel contains a larger area of the object being imaged. Thus, the object space resolution is found by the following equation.

\[
\text{object space resolution } \left( \frac{\text{lp}}{\text{mm}} \right) = \text{image space res. } \left( \frac{\text{lp}}{\text{mm}} \right) \times PMAG \tag{13}
\]

The units of lp/mm are useful when discussing resolution in terms of frequency, but practically, the spatial resolution is also expressed in units of microns (Imaging Resource Guide, 2014).

\[
\text{spatial resolution (um)} = \frac{1000 \left( \frac{\mu m}{\text{mm}} \right)}{2 \times \text{object space resolution } \left( \frac{\text{lp}}{\text{mm}} \right)} \tag{14}
\]
For resolution to have proper meaning, it needs to be defined at a specific contrast. Contrast, also known as modulation, is essentially the difference between black and white at a given resolution. Numerically, it can be defined as a percent in terms of the intensity of light collected in each pixel.

\[
\text{Contrast (\%) } = \left( \frac{\text{Max} - \text{Min}}{\text{Max} + \text{Min}} \right) \times 100
\]  

(15)

As the frequency of resolution increases, the sharp edge between a line pair becomes blurred because a lens cannot perfectly reflect light. Then the contrast is degraded resulting in grey pixels, and the ability to resolve fine details is lost (Imaging Resource Guide, 2014).

Resolution and contrast are also dependent on a lens’ light throughput. The amount of light allowed to pass through a lens is controlled by the lens iris, also known as the aperture. The aperture is measured by f-stop numbers (f/#).

\[
f/# = \frac{\text{effective focal length}}{\text{effective aperture diameter}}
\]  

(16)

As the f-stop number increases, less light passes through the lens. In general, f-stop numbers on a lens increase by factors of \(\sqrt{2}\). This results in the aperture’s area being halved, which decreases the light throughput in half, assuming uniform incoming light.

The f-stop number is dependent on working distance. The equation above is for objects at infinite distance. For imaging at a finite distance, the following approximation of working f/# is used (Imaging Resource Guide, 2014).

\[
(f/#)W \approx (1 + |PMAG|) \times f/\#
\]  

(17)
As light passes through the aperture, no matter the size, diffraction occurs. Diffraction results in an Airy Disc pattern, which for a point source of light looks like a bright disc (Airy Disc) with faint concentric rings. Diffraction results in decreased resolution and contrast. The diameter of the Airy Disc \(D\) can be calculated from the following equation where \(\lambda\) is the wavelength of light, \(v\) is the working distance, and \(d\) is the diameter of the aperture (Jacobson, 2000).

\[
D = \frac{2.44\lambda v}{d}
\]  

(18)

From the equation above, it can be seen that higher energy visible light, blue, will have less diffraction, and larger f-stop numbers will have greater diffraction.

Every lens has a diffraction limit. The theoretical resolution of a diffraction limited lens was proposed by Rayleigh in 1879. The Rayleigh criterion states two equal sources of light are resolvable when the principal intensity maximum of one Airy disc coincides with the first intensity minimum of the other Airy disc. Therefore, the resolution of a diffraction limited lens is one-half of the diameter of the Airy disc (Jacobson, 2000). This calculation does not account for contrast or manufacturing imperfections of lenses, which further degrade a lens’ performance.

\[
Resolution = \frac{1.22\lambda v}{d}
\]  

(19)

The f-stop also determines the depth of field, which is a lens’s ability to maintain resolution and contrast without refocusing as the working distance increases or decreases (Imaging Resource Guide, 2014). The depth of field is crucial with transparent objects,
like plastic scintillators, because it is necessary for the entire thickness of the scintillator to be in focus in order to maximize resolution. The f-stop number varies proportionally with depth of field. The larger the f-stop number is the larger the depth of field.

There is value in determining the theoretical resolution of imaging components, the sensor and lens, but the completed imaging system must be tested to determine the resolution. One test method is using the 1951 United States Air Force (USAF) Resolution Targets. In general, the target consists of several different frequencies of line-pairs labeled by numbers representing groups and elements which correspond to a table of spatial frequencies in lp/mm.

To use the test target, a photo is taken of the target. Then the smallest resolvable element is determined by the ability to distinguish and count the smallest pattern of horizontal and vertical bars while maintaining the ability to count all larger elements. The observer may use magnification in order to determine the smallest resolvable pattern. Still, the observer
must be able to resolve all larger groups because of spurious resolution, which is an optical anomaly, where small patterns can be resolved and larger patterns cannot (USAF-1951 Standard Resolution Target T-20, n.d.).

A second way to determine the resolution of an imaging system is by determining the modulation transfer function (MTF) of the imaging system. The MTF is commonly used to characterize x-ray medical imaging systems and is becoming more widely used for neutron imaging (Tobin, 2009). Buhr (2003) states, “The Modulation Transfer Function is a basic performance measure of an imaging system describing the signal transfer characteristic of the system as a function of spatial frequency.” The method used in this research to determine the MTF utilizes the edge spread function (ESF). In MATLAB, a photo of an image with a distinct edge is loaded. Then, an average of pixel columns that contains the edge is calculated. This is the ESF, which is then differentiated to obtain the line spread function (LSF). The Fast Fourier transform of the LSF results in the MTF. The edge MTF technique has considerable noise because of the differentiation step. Even if the ESF is smoothed before differentiation, there remains an uncertainty in the MTF (Jacobson, 2000).

Figure 5: Edge method of determining the MTF

28
The result of the MTF is a graph of the contrast (modulation factor) against spatial frequency (lp/mm). Due to inherent noise in digital imaging, the minimum discernable resolution is at least 10% contrast (Imaging Resource Guide, 2014).

4.4: Noise

A digital image is subject to noise, which degrades the resolution and quality of an image. Noise is the generation and storage of non-light induced electrons (Jacobson, 2000). There are many contributors of noise: pixel non-uniformity, dark current, CCD read noise, and CCD Camera noise to name a few (Understanding CCD Read Noise, 2008). Furthermore, there are cosmic rays that can produce electrons in the CCD. Due to the inherent electronic noise in a CCD, an unexposed pixel does not have a zero value. According to Howell (2006), “the value for zero collected photoelectrons will translate, upon readout and A/D conversion, into a mean value with a small distribution about zero.” Therefore, to avoid negative ADU values in a picture, a positive offset is applied to pixel prior to exposure. This offset is referred to as the bias level. Fortunately, there are a variety of techniques to eliminate some of the noise in an image. In order to eliminate noise, digital image processing software must be used. This software enables the manipulation of each pixel value in an image or a series of images by a mathematical operation or an algorithm of commands. In this research, ImageJ, a free open source image processing software, was used.
The bias level, read noise, and camera (ADC) noise can be isolated by taking several zero second exposures in complete darkness. These are called bias frames. The average or median of these frames creates a master bias frame. Dark frames are simply frames shot in complete darkness for the length of exposure of the light image. The master bias should be subtracted from each dark frame. Once again, using a median or average of these frames produces a master dark frame, where the thermal noise, dark current, is isolated in the master dark frame.

Another technique to remove non-uniform pixel sensitivity, different quantum efficiencies for each pixel resulting from manufacturing defects in the lens or sensor, flat field frames can be taken. In this technique, a series of frames is taken where the sensor has uniform illumination. A good flat frame will match the color of the light being observed and will have less than two percent variation in pixel values. Once again, the bias frame should be subtracted from the flat field frames. Then the flat field frames should be averaged or a median taken, producing the master flat. Now with the bias, dark, and flat field frames complete, the raw image can be cleaned up immensely by the following equation (Howell, 2006).

\[
\text{Final Image} = \frac{\text{Raw Image} - (\text{Master Dark and Bias})}{(\text{Master Flat})}
\] (20)

As can be seen from this equation from Howell, the final image does not preserve the actual signal received in the original image. Therefore, by taking the mean pixel value of the master flat \( M \) and multiplying it by the equation, the pixel non-uniformity is
removed with the assumption of the same quantum efficiency for each pixel (Flat Field Correction, 2011).

\[ \text{Final Image} = \frac{(\text{Raw Image} - (\text{Master Dark and Bias})) \times M}{\text{Master Flat}} \] (21)

The file type of an image can also distort the pixel values. For instance, a JPEG file under-goes compression and information is lost, sometimes leaving behind artifacts (Long 2010). In scientific cameras, Raw or TIFF files are preferred because there is not a loss of information (Jacobson, 2000). In this research all files were saved as TIFF files.

The dynamic range and signal to noise ratio of a CCD are two values that are often used to describe the quality of a CCD and are both dependent on noise. The dynamic range of a CCD is the total range for which it is sensitive. It is expressed as the ratio of its full electron well depth to read noise, which is the brightest possible pixel value to the darkest possible pixel value. Essentially the dynamic range is the contrast ratio. Often the dynamic range is expressed in decibels. This simple ratio is easily converted to decibels by the following equation (Howell, 2006).

\[ \text{Dynamic Range (dB)} = 20 \times \log \left( \frac{\text{electron well depth}}{\text{read noise}} \right) \] (22)

While the dynamic range of a CCD characterizes its total range, the signal to noise (S/N) ratio describes the quality of signal in an image. Much of the noise associated with CCD cameras follow Poisson statistics, which simplifies the (S/N) ratio calculation.

\[ \frac{S}{N} = \frac{P}{\sqrt{P + n(N_B + N_D + N_R^2)}} \] (23)
In the preceding equation $P$ is the total number of photons collected in an image, $n$ is the number of pixels that contain $P$, $N_B$ is the number of background photons, $N_D$ is the number of dark current electrons, and $N_R$ is the number of read noise electrons (Howell, 2006).

4.5: Charge Transfer Efficiency (CTE)

While noise adds unwanted signal in an image, signal is lost during the transfer of charge in a CCD. The charge transfer efficiency (CTE) is the fraction of charge that is maintained from one pixel to another. These efficiencies are often greater than 0.99999, but the loss of charge can be significant depending on the number of transfers (Howell, 2006). The maximum number of transfers on a chip is simply the dimensions added together. In the case of a one mega pixel camera, assume the CCD has dimensions of 1,000 x 1,000. The last pixel read will have been transferred 2,000 times. If the charge collected in the last pixel was 10,000 electrons and the CTE is 0.99999, by the time it is read out, it would only have a charge equivalent to 9,800 electrons. The following equation corrects for the loss of charge during transfer for a single pixel.

$$Transfer\ Correction\ (CT) = \frac{ADU}{1 - \left( \text{#of Transfers} \times (1 - CTE) \right)}$$ (24)
4.6: Radiometry with Digital Cameras

Radiometry is the measurement of electromagnetic radiation, primarily light. The ability to accurately measure light in terms of photons is crucial in the characterization of experimental scintillators. In order to measure light, a detector must be used. In the field of astronomy, CCD cameras are commonly used to measure light emitted from objects in space and have an accuracy within one percent (Howell, 2006).

There are many factors in determining the number of photons emitted by an unmeasured light source. The first factor is uniformity of the light being emitted. Light sources are often assumed to be a Lambertian source, which means its radiance is constant regardless of the direction from which it is viewed (Rieke, 2003). Radiance is measured in Watts/m²/ster. In the case of PVT, it is assumed to be a Lambertian source because the light emitted is isotropic.

The second factor in determining light yield of a source is the geometry of the problem. The distance between the lens and the source, their radii, and their shape greatly affect how much light emitted by the source is detected by the camera. A spherical light source is a common geometry for radiometry. In the case the source is entirely in the field of view of the CCD camera, the power (number of photons) the lens receives is equal to the radiance in its direction multiplied by the source area, which appears as a circle, in the field of view times solid angle subtended by the lens as viewed from the source (Reike, 2003). In this case, the radiance in the direction of the lens is unknown, but the image provides the power received from the light source. Therefore, to find the radiance can be
simply found once the solid angle is determined. In this case, the solid angle calculation is as follows, where \( \theta \) is the half-angle of a right-circular cone whose base is the lens and whose vertex is on the surface of the light source (Rieke, 2003).

\[
\Omega = 4\pi \sin^2 \left( \frac{\theta}{2} \right)
\]

Once the radiance is found, the flux (\( S \)), the total photons emitted by the source, is simply found by multiplying the radiance (\( L \)) in the direction of the lens by \( \pi \) and the surface area of the source (\( A \)) (Reike, 2003).

\[
S = A\pi L
\]

An alternative method for determining the light yield of the source that avoids finding the radiance but solely relies on the number of photons recorded in the image (\( N \)) is as follows.

\[
S = N \frac{4\pi}{\Omega}
\]

These equations are only for spherical light sources. The analytical solutions for solid angles of other volume become quite difficult. For the geometry in this research, which Horowitz, Mordechai, and Dubi (1974) referenced, the solid angle calculation was prohibitively difficult, and therefore Monte Carlo methods were used to determine the solid angle. In this research, Monte Carlo Neutral Particle (MCNP6) was used to find the probability (\( P \)) of a single photon originating in a source arriving at the lens, essentially equal to \( 1/(4\pi/\Omega) \) from Equation 27.
While Equation 28 accounts for the light striking the lens, it assumes no other light losses are accrued from the lens to the sensor, while in reality there are several. Light is lost in the transmission through the lens, which is inherent to lenses and magnified by manufacturing defects. Also, as previously discussed, the quantum efficiency of the sensor is not 100%. Furthermore, the noise of the CCD inflates the pixel counts.

In this research, radiometry begins with an image, and therefore, the absolute light yield of an experimental scintillator must be calculated by working backwards. The following bulleted list describes this process.

1. Noise is removed from the imaged light source by at least subtracting bias and dark frames.
2. Each pixel ADU is multiplied by the gain of the sensor, which is the total number of electrons per pixel. Each electron is equivalent to one absorbed light photon.
3. All pixels are summed resulting in the number of photons detected \( N \).
4. \( N \) is then divided by the multiplied efficiencies of light transmission, charge transfer, and detection. These include quantum efficiency of the sensor, lens, f-stop, and mirror transmission efficiencies. This results in the total number of photons emitted from the PVT that entered the lens \( N_v \).
5. An MCNP6 simulation is done to calculate the probability (P) that a single photon of light generated in the PVT source enters the lens.

6. Finally, the total number of photons can be found by using Equation 28.

In this research, the absolute light yield only accounts for those photons that escape the scintillator. Therefore, any photons that are self-absorbed or internally reflected because of the material’s refractive index are not considered in the light yield. These are not counted because this light does not contribute to the light signal or imaging properties of the scintillator.
Chapter 5: Neutron Imaging Apparatus (NIA) Construction

In 2012, a member of the Nuclear Analysis and Radiation Sensor (NARS) research group installed a thermal neutron beam at the Ohio State Research Reactor (OSURR) in order to enhance neutron-based research. A first generation neutron imaging apparatus (NIA) was borrowed from the National Institute of Standards and Technology (NIST) in order to characterize the neutron beam profile and conduct initial neutron imaging experiments, but has since been returned. Therefore, based off of lessons learned from the first generation NIA and experimental requirements, a new NARS NIA was developed.

5.1: Light Tight Box Construction

The first generation light tight box was a fairly simple design. It was made from six pieces of quarter-inch thick anodized aluminum held together by many screws. The rigidity of quarter-inch panels enabled the far side of the box to be at a 45° angle in order to mount the mirror. At the front face of the box where the scintillator was mounted, a pocket was milled to approximately 1 mm in order to minimize neutron activation of the aluminum and the scattering of transmitted neutrons, which would degrade image resolution. Using the box revealed some design flaws. The most troubling was it leaked
light from where the camera cables entered the box. The leaking light degraded resolution with long exposures. The lid was designed to be screwed down, but that delayed adjustments inside the box during costly beam time. Therefore it was left unscrewed, which contributed to light leakage. Additionally, there was no way to ensure the camera was placed in exactly the same spot inside the box. The pocket was small and too close to the 45° angled side of the box, limiting scintillator and camera adjustment. Despite these issues, the first generation light tight box provided critical insight into the design of the NARS light tight box.

![Figure 6: The first generation light tight box](image)

Aluminum was a logical choice for a thermal neutron imaging light tight box because of its small neutron cross-sections, and was especially helpful for radiative capture, subsequent neutron activation, and low cost. The $\Sigma_a$ for the $^{27}\text{Al}(n,\gamma)^{28}\text{Al}$ reaction is .0141 cm$^{-1}$ and has a mean free path of 71.2 cm. The prompt gammas released from radiative capture have energy of 1.778 MeV. The half-life of $^{28}\text{Al}$ is 2.24 minutes. Therefore, after 22.4 minutes (10 half-lives), its activity is negligible. $^{28}\text{Al}$ decays by $\beta$
emission with a mean energy of 1.24 MeV to stable $^{28}\text{Si}$ (Basunia, 2013). Despite these radiations from activated aluminum, they are not prominent because of the small cross-section and thinness of the aluminum. Aluminum also has a relatively small $\Sigma_s$ (.087 cm$^{-1}$), which allows minimal degradation of resolution. The black anodized aluminum was chosen because of its flat black appearance which absorbs light and is not highly reflective. Also, the black coating is chemically bonded to the aluminum, providing durability and minimal additional atoms to interfere with imaging, as opposed to paint.

The anodized aluminum came in a sheet of dimensions 2’ x 2’ x 0.050” for $75 shipped. The thickness of the box material is only about 1.27 mm. This thickness was chosen to decrease the activation of the aluminum and scattering of the neutrons. The base of the box is made from standard aluminum with a thickness of 3.175 mm.

The box design was a simple rectangle. The sides and the rear of the box are all made from one piece of aluminum through 90° bends. All of the box’s joints overlap so that light cannot easily stream in. All the sides are bent under the base and secured with 4 screws. In the front, the imaging side of the box bends around the two sides and is attached near the top with a screw on each side. The lid of the box is bent all around its edges in order to slide on top of the box. Black aluminum tape was used to seal all mating surfaces of the box except the lid. On the right side of the box, a single hole was drilled in order for the camera cables to enter the box. The aluminum tape was used to tape down the cables and cover the hole to ensure light tightness. Lastly, the front of the box was milled on the outside to a thickness of approximately 0.020” or 0.5 mm. This was done
on the outside of the box in order for ease of mounting the scintillator on the inside of the box and maintaining a black finish on the inside of the box. This also greatly reduced the neutron absorption and scattering by the aluminum prior to the neutrons interacting with the scintillator so that the resolution would not decrease. The following table depicts the increased transmission rate for thermal neutrons when compared to the first generation light tight box.

<table>
<thead>
<tr>
<th>Description</th>
<th>Thickness (mm)</th>
<th>Absorption</th>
<th>Scattering</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Gen Side</td>
<td>6.35</td>
<td>0.9911</td>
<td>0.9460</td>
<td>0.9376</td>
</tr>
<tr>
<td>1st Gen Pocket</td>
<td>1.0</td>
<td>0.9986</td>
<td>0.9913</td>
<td>0.9899</td>
</tr>
<tr>
<td>NARS Side</td>
<td>1.27</td>
<td>0.9982</td>
<td>0.9890</td>
<td>0.9872</td>
</tr>
<tr>
<td>NARS Pocket</td>
<td>0.51</td>
<td>0.9993</td>
<td>0.9956</td>
<td>0.9948</td>
</tr>
</tbody>
</table>

The mirror selected for the box was an aluminum coated optical flat mirror from Edmund Optics. It is designed to be mounted at a 45° angle in order to bend light 90°. The mirror reflects over 90% of visible light (400-700 nm). In this research, the wavelength of light from the PVT is 611 nm, of which this mirror reflects at 92%. The mirror has dimensions of 127 mm × 178 mm in order to capture large images. The mirror was mounted in the box using an aluminum mounting bracket that was taped down to the base of the box to ensure 90° vertical mounting and easy removal. Using simple geometry, the mirror was mounted at a 45° angle by ensuring the mirror was equidistant from the front side and rear of the box.
Initial testing of the light tight box revealed two major issues: there was a light leak and the camera overheated in the box. The light leak was solved by placing black foam door seal, which can be purchased from any home repair store, to the edge of the lid so that the box would compress the foam forming a light tight seal.

Figure 7: (left to right) Lid/box interface, Light leak, Improved lid design

In order to keep the camera cool, two 50 mm cooling fans were mounted to the side of the box behind the camera. In order to keep light from streaming in from the cable and fan holes, a light stop was made. The light stop essentially divides the box into two compartments: the cooling side and the light tight side. The light stop only allows the lens of the camera to penetrate the light tight side of the box.

Figure 8: (left to right) Light stop, Light stop with camera, Light stop in box
The light stop provided the capability to ensure the camera maintained the exact working distance for experiments. This was possible because the light stop rested against the mirror mounting base. In order to test up to 10 different working distances, each approximately 1 cm further back than the previous, rectangular anodized aluminum spacer plates were placed between the mirror base and the light stop. The longer working distances enabled larger objects to be completely captured in the frame. Thus, the design of the light tight box was complete.

![Figure 9: Final NARS NIA with spacers](image)

5.2: Camera and Lens Selection

As seen in Figure 6, the camera used with the first generation imaging box was a point-shoot digital canon camera. It was a color camera, which degrades overall quantum efficiency because each pixel has either a red, blue, or green filter over it. The camera then interpolates the data to give color. The camera, when used for longer exposure
times, generated significant amplifier glow in the pixels near the ADC, which gave the
effect of over exposure in a corner of the frame. This camera was used for a proof of
principle, but could not be used for scientific applications and was more than likely the
source of resolution degradation.

The camera selected for the NARS NIA is the QSI 628s cooled-CCD camera
from Quantum Scientific Imaging. It can cool the sensor to 40°C below ambient by using
a two-stage thermoelectric cooler subsystem. This significantly reduces dark current
during long exposures. The dark current is quoted as <0.002 electrons/s at -10°C. The
sensor is the Sony ICX674ALG, which is a monochrome (black and white), 2.8
megapixel (4.54 µm square pixels), 16 bit, interline transfer CCD sensor. It has micro-
lenses to boost its peak quantum efficiency to 77% at 560 nm (QSI 628, 2013). Despite
its many excellent features, an interline CCD has a reduced quantum efficiency because
of the opaque pixels which transfer the data. Therefore, they are not preferred for
scientific imaging (Durini, 2014). Although micro-lenses significantly improve the
quantum efficiency, they can reduce resolution since the incoming light is focused into an
active pixel. The electron well depth of the camera is also small, approximately 22,000
electrons, which makes it easy to saturate the pixels. The main reason to purchase this
specific model of camera was cost. It was just over $3,000. Cooled-CCD cameras for
scientific applications can cost easily over $50,000, but this research is an intermediate
step in the neutron imaging process to assess whether or not to progress to high-end
imaging applications.
The camera uses a 25 mm Techspec compact fixed focal length lens from Edmund Optics. A fixed focal length lens was selected because they achieve the best performance within their field of view (Jacobson, 2000). This lens was selected because of its minimal working distance of 100 mm which yields a frame size of approximates 35 mm x 26 mm (19.8° field of view). It could still capture a small 1” scintillator in its entirety yet maximize the majority of its pixels for the image. The aperture has several stops ranging from f1.4 to f17 to control light throughput. The lens also has excellent contrast: 40% at the Nyquist frequency of the camera’s sensor’s pixel size of 110 lp/mm, which corresponds to 18.5 µm resolution. Furthermore, the lens has an excellent light transmission rate of >85% because of its antireflective coating. Also, the relative illumination, the ratio of brightness from the edge of the sensor to the center of the sensor, is greater than 95% for f-stop 2.8 and above.
5.3: Scintillator Design

The final aspect of the neutron imaging apparatus is the scintillator. Lawrence Livermore National Laboratory (LLNL) is in the process of developing PVT scintillators specifically designed for fast neutron imaging. PVT and other organic scintillators are often used for high count rate applications because of their extremely short decay time of 2.5 ns despite their low light yield. For imaging applications, however, light yield is more important than decay time. Therefore, the LLNL scintillators designed for fast neutron imaging are made with a europium-based spin-orbit coupling fluor, which has a millisecond decay time, but is able to harvest both singlet and triplet excitons in the scintillator due to the mixed character of its lowest excited state. The europium fluor emits a red light at about 611 nm. The anticipated light yield of these scintillators is about three times that of standard PVT. Therefore, one goal of this research is to utilize the NARS NIA to characterize the light yield of the PVT scintillators with the Eu fluor.

Prior to LLNL finalizing the scintillator design, some preliminary work was performed to decide the optimal thickness of the scintillators and to compare the energy deposition between PVT with and without $^6$Li-loading for fast neutrons. MCNP6 simulations were conducted to determine the energy deposition in the scintillators for different energies of fast neutrons and different thicknesses. The neutron energies were determined by fast neutron energies of convenience and interest. The Air Force Institute of Technology has a D-D neutron generator that produced 2.45 MeV neutrons, and 14 MeV neutrons are produced by the D-T neutron generator tubes that are commercially
available (Kapadia, 2009). Neutrons of energy 1.0 MeV were selected in order to approximate the response of the scintillators to low energy fast neutrons.

![Fast Neutron Energy Deposition](image)

Figure 11: Fast neutron energy deposition

The simulation results show energy deposition increases with increasing neutron energies because the recoil proton’s average energy is increasing, and the scattering cross-sections for all the elements is dominant. The energy deposition also increases with scintillator thickness because there are more neutron interactions.

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>1 MeV (%)</th>
<th>2.45 MeV (%)</th>
<th>14 MeV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.68</td>
<td>0.94</td>
<td>1.29</td>
</tr>
<tr>
<td>10</td>
<td>5.01</td>
<td>1.23</td>
<td>1.31</td>
</tr>
<tr>
<td>20</td>
<td>9.04</td>
<td>2.13</td>
<td>1.36</td>
</tr>
</tbody>
</table>

Table 5: Change in Energy Deposition with Lithium Loaded PVT
As can be seen in Table 5, the energy deposition was greater for the lithium loaded PVT scintillators for all energies and thicknesses. For neutron energies above 1 MeV, the gap in energy deposition decreases. As anticipated, more energy was deposited in the scintillators as the thickness increased, because there are more neutron interactions. The lithium loaded PVT energy deposition increases significantly from 5 mm to 20 mm for 1 MeV and 2.45 MeV neutrons because the cross-section of the $^6$Li charged particle reaction is still fairly large. This interaction yields much more energy than the average proton recoil for those energies. Furthermore, lithium loading primarily decreases the atom density of carbon. Therefore, in a scattering event with lithium, which becomes lithium’s dominant reaction, a neutron can impart 49% of its energy, which is much more energy than can be imparted to a carbon atom. Also, a secondary interaction is likely with 1 MeV and 2.45 MeV neutrons, because the mean free path ($1/\Sigma_t$) is 2.8 cm and 4.8 cm respectively; therefore, more energy is deposited in the thicker scintillators. For 14 MeV neutrons, the percentage of increased energy deposition for the lithium loaded PVT compared to the standard PVT is nearly constant for all thicknesses. This is primarily due to the 10.2 cm mean free path of 14 MeV neutrons, which makes secondary interactions unlikely. Furthermore, the $^6$Li charged particle reaction is not very likely. Thus, the reason for the gain in energy deposition of the lithium loaded PVT is that lithium displaces carbon, and a neutron can impart much more energy to a lithium atom than a carbon atom.

The amount of energy deposited in the scintillator is not as important as which element interacts with the neutron, because light yield decreases with heavier charged
particles and the amount of energy a charged particle can receive from a neutron also decreases. Therefore, using a thickness of 5 mm, the amount of energy received by each element in PVT from incident neutrons was calculated using MCNP6 simulations. The results showed about two percent of the energy deposited in the lithium loaded PVT for all neutron energies went to heavy elements that are introduced with lithium loading and produce little light. Correcting the energy deposition for energy only deposited to light producing recoil nuclei: hydrogen, lithium, and carbon, showed lithium loading only increased the energy deposition in PVT for 1 MeV neutrons. The increase in energy deposition was only about one percent for 1 MeV neutrons, while the decrease in energy deposition for 2.45 MeV and 14 MeV neutrons was about one percent.

In the end, when relating energy deposition to light yield, hydrogen economy is paramount. For 1 MeV neutrons, 62% of initial scattering events are with hydrogen. Yet for 14 MeV neutrons, the initial scattering events drop to 36% because the cross-sections significantly change for each element and interaction as incident neutron energies change. Despite this drop in hydrogen scattering events, the average energy of a recoil proton is much higher for 14 MeV neutrons, such that more total energy is imparted to recoil protons than with 1 MeV neutrons.

The conclusion from this preliminary research was that lithium loading does not significantly increase or decrease the light yield of PVT for fast neutron energies of 1, 2.45 and 14 MeV. Based on this initial work and prior research, LLNL decided an intermediate step of testing scintillators was needed to determine the final design of the
fast neutron imaging scintillator. Therefore, LLNL created a variety of scintillators to be tested for thermal and fast neutron imaging applications.
6.1: Camera Dynamic Range Validation

The CCD camera came with two preset gain settings: high and low. Prior to any imaging experiments, it was necessary to determine which gain setting had the greatest dynamic range. The test was fairly simple. A light was placed in front of the camera so that the sensor would be saturated for a very short exposure time. A frame was taken with each gain setting, and the average saturated pixel was found. The gain was then multiplied by the average pixel value to determine the effective electron well depth. The read-out noise was supplied by QSI, and then using Equation 22 the dynamic range was found. As can be seen in Table 6 a gain setting of 0.664 yielded the greatest dynamic range and was utilized for all images in this work.

<table>
<thead>
<tr>
<th>Gain</th>
<th>Average ADU</th>
<th>Electrons</th>
<th>Read Noise</th>
<th>Dynamic Range (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.664</td>
<td>31,559</td>
<td>20,955</td>
<td>4.640</td>
<td>73.1</td>
</tr>
<tr>
<td>0.296</td>
<td>65,535</td>
<td>19,398</td>
<td>4.532</td>
<td>72.6</td>
</tr>
</tbody>
</table>
6.2: Frame Size Calibration

The working distance and frame size in terms of spatial length are essential components to resolution calculations. For the best resolution, an object needs to fill the frame, utilizing as many pixels as possible. Therefore, the frame sizes at the 10 different working distances were determined experimentally by capturing the frames’ horizontal length with a ruler mounted where the center of the scintillator would be. The working distance was calculated from the frame size and the field of view angle of the lens. The following table presents the results from the multiple working distances available in the box. The 10 mm spacer was used for the testing of the scintillators because the entire scintillator would fit in the frame and maximize the frame space of the signal of light.

Table 7: NIA Frame Sizes at Each of the 10 Working Distances

<table>
<thead>
<tr>
<th>Approximate Spacer Widths (mm)</th>
<th>Vertical Frame Size (± 0.1 mm)</th>
<th>Horizontal Frame size (± 0.1 mm)</th>
<th>Working Distance (± 0.3 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>30.4</td>
<td>40.0</td>
<td>114.6</td>
</tr>
<tr>
<td>20</td>
<td>32.9</td>
<td>43.7</td>
<td>125.2</td>
</tr>
<tr>
<td>30</td>
<td>35.8</td>
<td>47.4</td>
<td>135.8</td>
</tr>
<tr>
<td>40</td>
<td>38.3</td>
<td>51.0</td>
<td>146.1</td>
</tr>
<tr>
<td>50</td>
<td>41.0</td>
<td>54.7</td>
<td>156.7</td>
</tr>
<tr>
<td>60</td>
<td>43.6</td>
<td>58.6</td>
<td>167.9</td>
</tr>
<tr>
<td>70</td>
<td>46.5</td>
<td>62.2</td>
<td>178.2</td>
</tr>
<tr>
<td>80</td>
<td>49.2</td>
<td>65.0</td>
<td>186.2</td>
</tr>
<tr>
<td>90</td>
<td>51.9</td>
<td>68.5</td>
<td>196.2</td>
</tr>
<tr>
<td>100</td>
<td>54.6</td>
<td>72.3</td>
<td>207.1</td>
</tr>
</tbody>
</table>
6.3: MTF and Resolution Calibration

The MTF calculated from the edge spread function is the method used in this research to characterize the resolution of the NARS NIA which included the neutron beam quality, scintillators, lens, and camera. In order to validate the use of this technique, the intrinsic resolution of the optical system was determined with a standard optical photography resolution test target. The target selected was the 1951 USAF Resolution Test Target. The test target was made on float glass with a chrome opaque coating, where the line pairs were transparent. At first, the test target was imaged in the light tight box where the scintillator would be placed. The image suffered from multiple light reflections because the chrome on the test target was reflective, making it difficult to discern the resolution. Therefore, the test target was taken out of the box and back-lit by a common desk lamp. A piece of white paper was slid between the test target and the desk lamp to diffuse the light, making it more uniform. Excess light was blocked using aluminum tape. The focus and f-stop (2.8) was maintained on the lens to ensure the same focus and light throughput was maintained outside of the box.

Figure 12: (left to right) Glass test target, Resolution test setup of camera and lens
As can be seen above in Figure 12, the working distance was approximately 115 mm which is nearly the same as calculated from the frame size calibration (114.6 mm). The frame width of this experimental set up was only 39.4 mm, whereas the frame width in the light tight box was 40.0 mm. The difference in frame width is likely due to the mirror in the light tight box. The image reflected in the mirror is slightly compressed resulting in a slightly larger field of view. Therefore, this experiment can only be used to validate the MTF method and the resolution of only the camera and lens in the imaging system. The resolution for the entire optical system would be tested later.

The theoretical resolution of the camera was also tabulated as a starting point for the expected resolution using Equations 11, 12, and 13.

\[
\text{image space resolution } \left( \frac{lp}{mm} \right) = \frac{1000 \left( \frac{lp}{mm} \right)}{2 \times \text{pixel size (4.54μm)}} = 110.1 \text{pl/mm}
\]

\[
PMAG = \frac{\text{horizontal sensor size (8.81mm)}}{FOV (39.4mm)} = .224
\]

\[
\text{object space res. } \left( \frac{lp}{mm} \right) = \left( 110.1 \frac{lp}{mm} \right) \times PMAG(.224) = 24.7 \text{ lp/mm}
\]

This resolution corresponds to a 20.2 μm maximum resolution of the camera and lens. Using the USAF 1951 test targets, the smallest resolvable target was group 4, element 3, corresponding to 20.16 lp/mm (25 μm), for pixel saturations of approximately 96%, 37%, and 9%. The different pixel saturations were obtained by varying the length of exposures and by measurement of the average pixel values. Maximum pixel saturation was not used to avoid the effects of blooming in the higher spatial frequencies. As anticipated, the experimental resolution was less than the theoretical resolution due manufacturing
defects and diffraction. Figure 13 shows the images of each of the test targets highlighting the group 4, element 3 pattern. As can be seen, the higher frequency patterns become indistinguishable and uncountable, but determining the maximum group and element is somewhat subjective.

Figure 13: (left to right) 1951 USAF resolution test target images for 96%, 37%, and 9% pixel saturations

Using the same images from above, an edge was taken where each edge image had the same dimensions: 63 x 50 pixels. The pixel values were averaged into a single array ESF and smoothed. The MTFs were produced using the method previously discussed in chapter 4.3. The results are shown in Figure 14. Once again, the resolution determined by the 10% MTF was nearly the same for all three pixel saturations. However, the 10% MTF resolution was only 17.5 lp/mm, which is about 13% less than the test target resolution. The constant resolution, despite the large differences in pixel saturations, was an unanticipated result for both the test target and MTF. It was assumed the pixel saturations were proportional to contrast. Therefore, the 37% and 9% pixel saturations were expected to have a decreased resolution.
Figure 14: MTFs for 96%, 37%, and 9% pixel saturations

Figure 15: ESFs for 96%, 37%, and 9% pixel saturations
In order to gain understanding of why the resolutions remained constant, the ESF and the contrasts of each imaged edge were examined. The edge spread functions are shown above in Figure 15. The contrast was calculated for each edge by using Equation 15, where the values were determined by the average value of the light pixels and the average value of the dark pixels. Table 8 summarizes the results of the contrasts, edge spread functions, and resolutions for each edge of varying pixel saturation.

<table>
<thead>
<tr>
<th>Image Edge</th>
<th>Pixel Saturation (%)</th>
<th>Contrast (%)</th>
<th>ESF (lp)</th>
<th>USAF Resolution (lp/mm)</th>
<th>MTF Resolution (lp/mm)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>96.3</td>
<td>95.0</td>
<td>2</td>
<td>20.16</td>
<td>17.7</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>37.3</td>
<td>93.7</td>
<td>2</td>
<td>20.16</td>
<td>17.5</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>8.7</td>
<td>75.8</td>
<td>2</td>
<td>20.16</td>
<td>17.3</td>
<td>14.2</td>
</tr>
</tbody>
</table>

Based on the data, the assumption that pixel saturation is proportional to contrast is false. The same edge was used for each photo. Therefore, the edge does not change, but the edge spread function does with respect to the contrasts as seen in Figure 15. All the edges span two line pairs, but within those four pixels the ESF varies greatly for each pixel saturation edge. The significant decrease (>10%/pixel) in the ESF for 96% and 37% pixel saturations each span one line pair, but the 96% pixel saturation ESF is much sharper. Thus, its 10% MTF resolution is slightly higher than that of 37% pixel saturation. The significant decrease of the 9% pixel saturation ESF spans 1.5 line pairs,
although its contrast is much lower than the others, but its MTF is only slightly lower than the others. Therefore, it can be concluded the distribution of the ESF is effected by contrast, which in turn only slightly affects the 10% MTF resolution.

Turkoglu, Cao and Lewnadowski in 2013 found similar results in their development of a low-cost neutron radiography device. Despite varying exposure times, the contrast did not appreciably change, and the resolution determined by an image edge 10% MTF remained nearly the same. Their camera was a non-cooled CCD camera, so for longer exposure times the dark current contributed greatly to the dark pixel values, which added to their lack of change in the contrast of the imaged edges. In fact, their longest exposure of 101 seconds had the worst contrast at 71% (Turkoglu, 2013).

Prior to making any final conclusions about the resolution accuracy of the ESF MTF, further testing was required to account for lower contrasts and what effect, if any, the NIA mirror has on resolution. Therefore, varying contrasts of 1951 USAF resolution targets were placed inside the NIA where the scintillators would be located. The camera and lens had the same focus, f-stop, and working distance as the previous test, which was the anticipated experimental setup for the LLNL PVT characterization experiment. The targets were printed on photographic paper and did not require back lighting. Therefore they could be imaged inside the box. These targets only reflected light, as opposed to being back-lit like the glass target. The experiment was conducted nearly the same as before, but the contrast was determined by the target instead of the exposure time. Each exposure was 50 ms.
The paper targets yielded the same maximum resolution, 20.16 lp/mm, as the glass targets when characterized by group and element number for contrasts of 68.8% and above. The corresponding 10% MTF resolutions were less than the actual resolution, but with an error twice that of the 10% MTF of the glass targets. The edges of the paper targets were not as sharp as the edges of the glass target, primarily due to toner bleed. The edge of the glass targets spread across only two line pairs while the edge of the paper targets spread across 5-6 line pairs. This resulted in the degradation of the 10% MTF for the paper targets, where the maximum resolution of 20.16 lp/mm could be determined. Figure 16, summarizes the 10% MTF resolution values to the USAF resolution values.

![MTF Resolution vs USAF Resolution](image)

Figure 16: NIA USAF and MTF resolution comparison

As seen in Figure 16, the 10% MTF resolutions only gradually decrease with contrast because the sharp edge of the paper target is essentially the same for each paper
target. Figure 17 shows the ESF for multiple edges of different contrasts. The ESF remains constant, but as the contrast decreases, the ESF within those 5-6 line pairs broadens. For contrasts above 37.6% there is only a 4% decrease in the 10% MTF resolution for this contrast range. For contrasts above 11.1% there is only a 17% change in the 10%MTF resolution. At 5.5% contrasts the 10% MTF drops sharply because the ESF has broadened in terms of line pairs.

![Paper Target Edge Spread Function Comparison](image)

Figure 17: USAF paper target ESFs for multiple contrasts
The USAF resolutions are only dependent on contrast. The nearly linear decrease in the USAF resolution enables the resolution be modeled using a piecewise defined function where $R$ is the resolution with respect to $c$ contrast.

$$R(c) = \begin{cases} 
20.16, & c \geq 68.8 \\
.188c + 7.226, & 28.7 \leq c < 68.8 \\
.3662c + 2.0629, & 5.5 \leq c < 28.7 
\end{cases} \quad (20)$$

This piecewise function for resolution has less than 4% error for all data points and an average error of 1.6%. The r-squared values of the second and third equations are 0.9944 and 0.9959 respectively.

Figure 18: USAF (actual) resolution vs Equation 20 modeled resolution
Equation 20 enables the resolution of an edge to be determined solely from its contrast found by Equation 15, where the values are the mean pixel values for the light and dark sides of an imaged edge. It is important to note that Equation 20 is specific to this imaging set up. In the event the f-stop, lens, working distance, or camera sensor is changed, the entire resolution to contrast calibration would need to be redone because the resolution of the imaging system may have changed. It is also only applicable to edges whose ESF is between 5-6 line pairs. The methodology behind Equation 20, however, could be repeated if resolution targets with edges that spanned varying amounts of line-pairs were created.

In light of the data acquired in this testing, the edge method MTF might not be a precise method for determining the resolution of an imaging system, especially at very low contrasts. However, based off the glass and paper targets, it can be extrapolated this imaging system has a maximum resolution of 20.16 lp/mm for edges spanning 2-5 line pairs and contrasts greater than 68.8%. An interesting observation, however, is the addition of the 10% MTF resolution and the number of line pairs the ESF spans for contrasts above 68.8% is a reasonable approximation of the actual resolution. For the glass targets, this approximation yields 19.7, 19.5, and 19.3 lp/mm and for the paper targets this yields 20.3 and 20.1 lp/mm. Further research would need to be conducted to determine the extent of this relationship. In conclusion, the 10% MTF based off the ESF has merit, since it tends to underestimate the actual resolution for a fairly broad range of contrasts, especially as the ESF broadens. It is a simple method to get a reasonable first approximation of an imaging systems resolution.
Chapter 7: PVT Testing

LLNL provided seven different scintillators to be tested in order to finalize the dimensions and composition of the fast neutron imaging scintillator. Table 9 summarizes the scintillators’ thicknesses and light yields. The light yield of PVT (Eu) is unknown but anticipated to be two to three times higher than that of standard PVT. An Eu doped Gd-Lu-bixbyite (GLO) ceramic was also received to test for its response to thermal neutrons. This scintillator was developed for gamma spectroscopy and it may also prove to be an excellent thermal neutron imager because of its gadolinium content (Cherepy, 2015).

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Thickness (mm)</th>
<th>Light Yield (Photons/MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVT</td>
<td>5.9</td>
<td>10,000</td>
</tr>
<tr>
<td>Lithium loaded PVT 1.3% $^6$Li</td>
<td>2.2</td>
<td>10,000</td>
</tr>
<tr>
<td>Lithium loaded PVT 1.9% $^6$Li</td>
<td>3.3</td>
<td>10,000</td>
</tr>
<tr>
<td>PVT with Eu fluor</td>
<td>2.0</td>
<td>20,000-30,000 (anticipated)</td>
</tr>
<tr>
<td>PVT with Eu fluor</td>
<td>1.0</td>
<td>20,000-30,000 (anticipated)</td>
</tr>
<tr>
<td>GLO (Eu)</td>
<td>0.15</td>
<td>55,000</td>
</tr>
<tr>
<td>ZnS(Ag) PVT</td>
<td>1.0</td>
<td>160,000</td>
</tr>
</tbody>
</table>
7.1: The OSURR

The OSURR has a collimated thermal neutron beam with a maximum flux of 4.4 \( \times 10^6 \) n/cm\(^2\)/s at the imaging plane (OSURR, 2016). A 5” long single-crystal sapphire was installed in the beam line to scatter fast neutrons out of the beam while allowing thermal neutrons to pass (Turkoglu, 2012). The cadmium ratio is 92 and the fast flux is 4.8 \( \times 10^4 \) n/cm\(^2\)/s at 450 kW (OSURR, 2016). The fast neutron energy spectrum is assumed to be similar to the Watt spectrum. The circular beam has a uniform maximum flux across an approximately 3.5 cm diameter umbra (Turkoglu, 2012). Therefore, the scintillators with a one-inch diameter can be placed fully within the umbra of the beam and receive an uniform flux.

The thermal neutron beam also contains gamma photons, and a 6” long polycrystalline bismuth filter was placed in the beam collimator to attenuate the gamma content. The attenuation equation for gamma photons is nearly the same as that for neutrons, but the macroscopic cross-section is replaced with the linear attenuation coefficient (\( \mu \)).

\[
I = I_o e^{-\mu x}
\]  

(29)

The poly-crystalline bismuth effectively filters nearly all of the incident photons of 0.5 MeV and below from the beam. The transmission of uncollided 2 MeV photons is approximately 1%, while the maximum uncollided transmission of photons at 4 MeV is 1.6% (Turkoglu, 2012).
The OSURR neutron beam facility was used to test the scintillators’ response to thermal and fast neutrons. For thermal neutron imaging, the light yield contributions from fast neutrons and photons were neglected because they were relatively small compared to the light yield of the charged-particles produced by $^6$Li neutron capture reaction. For fast neutrons, the ability to distinguish between light yield contributions from the fast neutrons and photons is not possible because the gamma spectrum is unknown.

7.2: Thermal Neutron Imaging

Thermal neutron imaging techniques were used to determine how the thickness of transparent scintillators affects resolution and how different $^6$Li-loading affects light yield. Four different scintillators were used for this experiment. Two samples are made of $^6$Li-loaded PVT, the first of which has a thickness of 3.3 mm and 1.9% $^6$Li (by weight) and the second of which has a thickness of 2.2 mm and 1.3% $^6$Li (by weight) (Cherepy, 2015a). The third sample is a standard PVT scintillator with a thickness of 5.9 mm to be used as a control sample for the fast neutron and gamma responses. The fourth sample is a GLO scintillator. The PVT samples are hereafter referred to by their thicknesses and $^6$Li weight percentages, for example, PVT (3.3 mm, 1.9%), PVT (2.2 mm, 1.3%), and PVT (5.9 mm).

In order to test the resolution, a gadolinium foil, 0.127 mm thick with a sharp edge, was placed outside on the surface of the imaging box. The Gd foil absorbs the thermal neutrons while allowing the fast neutrons and gammas to pass. The area of the
PVT covered by Gd would only produce a small amount of light compared to the light produced by the surrounding $^6\text{Li}$-loaded PVT exposed to thermal neutrons. The experimental setup is shown below.

![Experimental setup, Gd foil](image)

Figure 19: (from left to right) Experimental setup, Gd foil

In order to reduce the noise from the gamma interaction with the CCD camera sensor, ten 60-second frames were taken of each scintillator. The frames were then processed to remove the significant “white spots” noise produced by gamma rays and summed to increase the signal to noise ratio. The final pictures, shown below in Figure 20, are contrast adjusted so that features can be distinguished. Figure 21 shows the same set of pictures with an ADU density plot. The PVT scintillators are on the same scale in order to show their relative light intensities.
Figure 20: Thermal neutron image of a thin Gd foil: (from left to right) PVT (3.3 mm, 1.9%), PVT (2.2 mm, 1.3%), PVT (5.9 mm), and GLO (0.15 mm)

Figure 21: Thermal neutron relative light yield: (from left to right) PVT (3.3 mm, 1.9%), PVT (2.2 mm, 1.3%), PVT (5.9 mm), GLO (0.15 mm)

In terms of light yield, the results are as anticipated, except for the PVT (5.9 mm), which shows a reversed effect on the light produced. As seen in Figure 21, the PVT (5.9 mm) shows a brighter profile behind the Gd. The thermal neutrons would not produce light in the PVT (5.9 mm), because there is no lithium loading in a pure PVT. Therefore, the faint beam profile outside the Gd covered region is anticipated from fast neutrons and gammas interactions with PVT. In reality, the neutron capture of Gd produced a spectrum of prompt gammas and internal conversion electrons (ICEs). The most prominent prompt gamma has an energy of 0.247 MeV, and is emitted 22.18% of the time a neutron is absorbed (Senftle, 1971). The most abundant ICEs have an energy of 71 keV, which has a maximum range of 20.6 µm in Gd (Kandlakunta, 2012). Therefore, most of the ICEs are stopped in the Gd. The ICEs that escape the Gd are more than likely stopped in the
aluminum window which has a thickness of 0.5 mm. The average path lengths in
aluminum for the 71 keV ICE and 191 keV ICE, the most energetic ICE of Gd, are 48
µm and 215 µm respectively (ESTAR, n.d.). The light coming from PVT under the Gd is
attributed to the prompt gamma rays produced by Gd neutron capture and the X-rays
produced from aluminum’s interaction with ICEs and gamma rays.

In order to compare the light yields of PVT with different lithium loadings, the
light yield, in terms of ADUs, was normalized to the thickness (mm) of each scintillator.
Table 10 summarizes the results, where it shows the PVT (3.3 mm, 1.9%) yields 4.5%
more light per mm than the PVT (2.2 mm, 1.3%).

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Mean Pixel Value* (ADU)</th>
<th>Light Yield (ADU/mm)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVT (2.2 mm, 1.3%)</td>
<td>661.9</td>
<td>293.6</td>
<td>0.021</td>
</tr>
<tr>
<td>PVT (3.3 mm, 1.9%)</td>
<td>1,028.7</td>
<td>306.9</td>
<td>0.025</td>
</tr>
<tr>
<td>GLO (0.15 mm)</td>
<td>3,327.4</td>
<td>14,717.6</td>
<td>0.003</td>
</tr>
<tr>
<td>Background</td>
<td>7.9</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* value is averaged over 240,000 pixels

The effect of scintillator thickness on spatial resolution was examined by
comparing the ESF and the 10% MTF values of the PVT (3.3 mm, 1.9%), PVT (2.2 mm,
1.3%), and GLO (0.15 mm). The ESFs were determined from a certain area of pixels (63
x 50) centered on the edge of the GLO (0.15 mm), which is fixed for all other
scintillators. Therefore, the consistence for a fair comparison is maintained because the
Gd position, the camera’s position, and the field of view are all fixed for each image. As
seen in Figure 22, the thicker scintillators’ edges are broader than the GLO’s edge. This
is expected because light spreading in a thicker scintillator is more profound than that of a thinner scintillator, which produces a less sharp edge. The thicker scintillators’ ESFs also shifted to the right of the GLO edge. The ESF of PVT (2.2 mm, 1.3%) shifted by 2 line pairs and the ESF of PVT (3.3 mm, 1.9%) shifted by 3 line pairs. These shifts correspond to 0.08 mm and 0.12 mm, respectively. This effect appears to be linear, where each mm of thickness corresponds to about one line pair. This linearity in the shift of the ESFs implies the imaging plane is not normal to the beam. This may be a result of the light tight box being slightly warped, or the borated polyethylene collimated sheets are not normal to the beam.

Figure 22: Scintillator ESF comparison showing the broadening and shifting of the edges of thicker scintillators
For a better comparison of the ESFs, the edges were centered on the GLO edge, and an ESF corresponding to a USAF paper target under ambient light with similar contrast to the GLO was added. As seen in Figure 23, the GLO ESF is nearly identical to the USAF paper target ESF. Therefore, Equation 20 can be used to determine the actual spatial resolution of the GLO. It becomes difficult to visually compare the broader ESFs of the PVT scintillators. Therefore, each ESF was measured by its “heal to toe” distance. This distance was determined by the number of line pairs whose values fell within 10-90% of the normalized pixel values. The PVT (2.2 mm, 1.3%) ESF spanned 12 line pairs and the ESF of the PVT (3.3 mm, 1.9%) spanned 12.5 line pairs.

![Final Scintillator ESF Comparison](image)

Figure 23: Centered scintillator ESFs comparison
The MTF of these image edges are shown below in Figure 24, and the results of the effect of scintillator thickness on spatial resolution and $^6$Li-loading are summarized in Table 11.

![Scintillator Modulation Transfer Function](image)

**Figure 24**: Thermal neutron scintillator resolution comparison

<table>
<thead>
<tr>
<th>Description</th>
<th>Contrast (%)</th>
<th>MTF Resolution (lp/mm)</th>
<th>Corrected Resolution (lp/mm)</th>
<th>Error (%)</th>
<th>Resolution (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLO (0.15 mm)</td>
<td>37.4</td>
<td>14.7</td>
<td>14.3</td>
<td>11.2</td>
<td>35.0</td>
</tr>
<tr>
<td>Paper Edge</td>
<td>37.6</td>
<td>14.7</td>
<td>14.3</td>
<td>11.2</td>
<td>35.0</td>
</tr>
<tr>
<td>PVT (2.2 mm, 1.3%)</td>
<td>32.7</td>
<td>10.9</td>
<td>-</td>
<td>-</td>
<td>45.9</td>
</tr>
<tr>
<td>PVT (3.3 mm, 1.9%)</td>
<td>28.2</td>
<td>9.7</td>
<td>-</td>
<td>-</td>
<td>51.5</td>
</tr>
</tbody>
</table>
The PVT (2.2 mm, 1.3%) resolution was better than that of the PVT (3.3 mm, 1.9%), as anticipated because it is thinner and its ESF spanned less line pairs. The PVT (3.3 mm, 1.9%) has the worst contrast, because more light was produced behind the Gd foil due to its thickness and higher $^6$Li-loading. Also the thicker scintillator enables light spread inside the scintillator, further decreasing its contrast. If the PVT (3.3 mm, 1.9%) edge was normalized to a thickness of 2.2 mm, its contrast would only increase to 30%. This would still be lower than PVT (2.2 mm, 1.3%) and would do little to enhance its 10% MTF resolution.

The GLO scintillator had the exact same 10% MTF resolution as the paper target edge of similar contrast and ESF. This demonstrates the neutron beam is well collimated and presents negligible degradation to the MTF compared to using a paper target in ambient room light. The corrected resolution for the GLO was 14.3 lp/mm, which corresponds to 35.0 µm. It is important to note that GLO is sensitive to gammas, but its response to thermal neutrons was significant as seen in Figure 20. The ratio of the dark to bright sides of the GLO Gd foil edge was 45.5%. This implies at least 54.5% of its light yield was due to the thermal neutron capture of the Gd in the GLO, which produces prompt gammas and conversion electrons that efficiently produce light. The error associated with the corrected resolution seems high but, as previously mentioned, the 1951 USAF test target is subjective and the lp/mm corresponding to the patterns increase or decrease by about 11.6% on average. More than likely, the actual resolution is within only one step of the observer’s reported value. In this research, I have tried not to overestimate the resolution from the test targets.
In conclusion, the $^6$Li-loading of 1.9% increases the light yield of PVT by 4.5% per mm compared to a $^6$Li-loading of 1.3%. The resolution degradation from a 3.3 mm thick PVT scintillator to a 2.2 mm is 1.2 lp/mm, an 11% decrease. Therefore, a compromise in the lithium loading and scintillator thickness can be made where light yield remains high but resolution and contrast do not suffer. GLO shows excellent promise as a thermal neutron imager. Even in the absence of gamma activity, it would produce about twice the light as the PVT (3.3 mm, 1.9%) scintillator and have superior resolution because of its 0.15 mm thickness.

7.3: Scintillator Response to Fast Neutron Spectrum

In order to conduct fast neutron imaging at the OSURR, a piece of 1 mm thick cadmium sheet was placed in front of the thermal neutron beam. The cadmium absorbs neutrons at 0.55 eV and below, leaving only the fast neutron spectrum, with an average energy of ~2 MeV. Initially, the cadmium was placed directly on the imaging window on the outside of the box, like the gadolinium, but the prompt gammas from the cadmium neutron capture produced a strong light signal, as seen below in Figure 25.
The prominent prompt gamma from Cd has energy of 0.559 MeV and is emitted nearly 80 times out of 100 neutron captures (Senftle, 1971). Fortunately, the light signal from Cd is half that of Gd. The scintillator did not cover the entire field of view in order to show a clear background signal, as well as any signal produced from the fast neutrons and gammas inherent to the reactor. Figure 25 demonstrates that there is a response from the fast neutron and gamma spectrums of the reactor.

In order to offset the density of the prompt gammas from Cd, the box was moved back as far as possible (2.3 cm) from the 1 mm thick cadmium sheet covering the beam. The first experiment conducted was to determine the difference in the light yield of the Cd covered beam and the open beam. The experimental set up and the density plot of the picture are shown in Figure 26. Half of the beam was covered with 1 mm thick Cd and the PVT (2 mm, Eu) scintillator was used. The PVT (2 mm, Eu) was used because of its anticipated higher light yield, which would provide a better contrast. Once again, 10 one minute pictures were taken, processed to remove noise, and added together to produce a final image. The density plot had much more noise than previous plots because of the decreased interaction rate in the PVT and relatively low light yields.
The density plot shows the uncovered side of the beam produced about 26% more light than the Cd covered beam. The decreased light yield of the covered beam is primarily due to the attenuation of beam photons by the cadmium, which is a high Z material. The gamma dose rate of the beam is $2.4 \pm 20\%$ rem/hr (Turkoglu, 2012). Due to the efficiency of the poly-crystalline bismuth filter in the beam, it is reasonable to assume the average energy of a photon in the beam is small. For instance, if the average photon energy in the beam is 0.3 MeV, then by Equation 29, 23% of the photons are attenuated by the Cd. Thermal and slow neutrons do not have enough kinetic energy to produce recoil nuclei with enough energy to excite and ionize the material around them. The $(n,\gamma)$ thermal neutron reactions of carbon and hydrogen in the PVT also contribute to the increased light yield. It is important to note that the increased light yield is only about 6 photons per pixel.

Despite being unable to distinguish the fast neutron light yield from the photon light yield, a comparison of relative light yields of the PVT based scintillators was conducted. The beam was completely covered by a 1 mm thick piece of Cd. Thus, every
scintillator was exposed to the same amount of fast neutrons, gamma photons from the reactor, and prompt gammas from the Cd. The same procedure previously described was performed to tabulate the results shown in table 12. Figure 27 shows the Cd covered beam.

Figure 27: 1 mm Cd covered beam

Table 12: Fast Neutron (OSURR) Light Yield

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Pixels measured</th>
<th>Mean Light Pixel (ADU)</th>
<th>Light Yield (ADU/pixel)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVT (5.9 mm)</td>
<td>1131016</td>
<td>88.78</td>
<td>13.83</td>
<td>0.109</td>
</tr>
<tr>
<td>PVT (2.2 mm, 1.3%)</td>
<td>1131016</td>
<td>46.62</td>
<td>17.93</td>
<td>0.076</td>
</tr>
<tr>
<td>PVT (3.3 mm, 1.9%)</td>
<td>1131016</td>
<td>66.22</td>
<td>17.89</td>
<td>0.082</td>
</tr>
<tr>
<td>PVT (2.0 mm, Eu)</td>
<td>1131016</td>
<td>40.93</td>
<td>16.88</td>
<td>0.102</td>
</tr>
<tr>
<td>PVT (1.0 mm, Eu)</td>
<td>1131016</td>
<td>18.45</td>
<td>11.27</td>
<td>0.150</td>
</tr>
<tr>
<td>ZnS (1.0 mm)</td>
<td>1131016</td>
<td>669.9</td>
<td>662.7</td>
<td>0.016</td>
</tr>
<tr>
<td>Background</td>
<td>538560</td>
<td>7.19</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The data shows the lithium loading significantly increases the light yield (ADU/mm) by 29% over PVT without lithium loading. Since the PVT (3.3 mm, 1.9%) is thicker and has a higher lithium loading than the PVT (2.2 mm, 1.3%), it was anticipated to produce more light. This was not the case; however, their light yields were nearly the same. It may be concluded that the lithium loading enhances light yields for fast neutrons,
but there is a threshold where the lithium loading decreases the light yield, which is more than likely the case of the PVT (3.3 mm, 1.9%). Since the energy of the prominent prompt gamma of Cd is known (0.559 MeV), the linear attenuation coefficient for this gamma energy for the three standard PVT scintillators with and without Li-loading were compared. This was done to see what effect the lithium loading had on the gamma response. There was not a significant difference in their linear attenuation coefficients. Therefore, it can be concluded the increase in the light yield of the lithium loaded PVT scintillators was due to fast neutron interactions with $^6$Li, especially the charged particle reaction caused by the absorption of epithermal neutrons in the beam. The charged particle reaction for $^6$Li remains the dominant reaction for neutrons with energy below 50 keV and remains significant for neutron energies below 300 keV. The slowing-down of fast neutrons by hydrogen and the subsequent absorption by $^6$Li also contributes to the increased light yield of the lithium loaded PVT scintillators.

The PVT (2 mm, Eu) produced nearly 50% more light/mm than that of the PVT (1 mm, Eu). Upon further investigation, the PVT (1 mm, Eu) has many optical defects, which contributed to its degraded light yield/mm. The PVT (2 mm, Eu) produced 22% more light per mm than the standard PVT (5.9 mm), which is much less than expected. The effect of thickness on overall light yield cannot be disregarded. It is unreasonable to assume scintillators of the same composition would respond linearly with regard to thickness, especially in response to gammas. Thicker scintillators not only have increased light yields because of increased interactions with gammas, but also because of their increased probability of having secondary Compton scattering and photo-electric
absorption events. These secondary events would increase their light yields substantially. Furthermore, since the gamma spectrum is unknown, it is possible that many gammas would hardly interact with a thinner scintillator, whereas their interaction with a thicker scintillator would be noticeable. Despite these many factors that may have skewed the magnitude of the light yield increase, it can be concluded the Eu fluor enhances the light yield of PVT. In order to accurately evaluate the magnitude of the light increase between standard PVT and PVT with a Eu fluor, either the scintillators would need to be the same size and thickness, or be exposed to a singular, monoenergetic radiation source.

7.4: Scintillator Response to 2.45 MeV Neutrons

A D-D neutron generator at the Air Force Institute of Technology was used to test scintillators, which is capable of producing $10^9$ n/s. The neutron energy is nearly monoenergetic at 2.45 MeV. A fast neutron intensity of $9.6 \times 10^8$ n/s was generated for the experiment. The experimental setup is shown below in Figure 28. The distance from the generator to the scintillator plane was 21.5 cm. Therefore, the flux at the scintillator was about $1.6 \times 10^5$ n/cm$^2$/s.
Experimenting with the generator proved to be difficult. It was very time consuming to get the fusion reaction and neutron intensity to stabilize, which only left a short amount of time for testing. Therefore, only the PVT (2 mm, Eu) and the PVT (5.9 mm) were imaged. The isotropic nature of the generator created a significant amount of noise in the initial images. Therefore, in order to minimize the dose to the camera’s sensor only five one-minute photos were taken. In the end, the camera’s sensor sustained some radiation damage, as seen by the vertical lines of hot, or dead pixels, in the processed photos.

The final images, adjusted for best contrast, are shown below in Figure 29. The PVT (5.9 mm) has a considerable amount of noise. The light signal is faint and can only be distinguished by a curved vertical line in the photo. The noise caused the background to have a higher mean ADU value than the scintillator’s side. Therefore, in order to derive the light signal of the scintillator, the median values of background and scintillator light signal were averaged for the PVT (5.9 mm) images. Hence, only a single averaged
photo is used to compare the PVT (2 mm, Eu) and PVT (5.9 mm) light yields. The normalized light yield comparison is shown in Table 13.

Figure 29: (left to right) PVT (5.9 mm), PVT (2 mm, Eu)

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Light Yield (ADU/mm)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVT (5.9 mm)</td>
<td>0.17</td>
<td>5.2</td>
</tr>
<tr>
<td>PVT (2 mm, Eu)</td>
<td>0.46</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The data shows the PVT (2 mm, Eu) yields 2.7 ± 0.2 times more light/mm than the PVT (5.9 mm), which is in agreement to the anticipated light yield, unlike the modest gain of just 22% for the fast neutron spectrum at the OSURR. The neutron generator has much less gammas ray contamination than the OSURR thermal beam, which may have distorted the scintillators’ responses at the reactor, yielding only a 22% gain in the light. The mean free path of the 2.45 MeV neutrons in PVT is 4.8 cm. Therefore, it is highly unlikely for either scintillator to undergo a secondary scattering event. Thus, the light yield was normalized, in a second way, by calculating the attenuation of 2.45 MeV neutrons in the PVT (5.9 mm) for thickness of 5.9 mm and 2 mm. The ratio of these
values provided the fractional decrease in the light yield of the PVT (5.9 mm), which normalized its light yield to the thicknesses of the PVT (2 mm, Eu). According to this data analysis, the PVT (2 mm, Eu) yielded 2.6 times more light than the PVT (5.9 mm). This value is in agreement with the original found value and within its margin of error.

An attempt to characterize the light yield of the PVT (2 mm, Eu) and PVT (5.9 mm) was made by utilizing the method described previously in Section 4.6. The CTE was determined by the average number of transfers a charge would be transferred in the sensor. A MCNP6 simulation provided the energy transferred to recoil protons in the scintillators, which is about 85% of the total energy deposition. The carbon recoil energy was neglected, because the light produced from carbon recoil nuclei from 2.45 MeV neutrons is minimal (Steuer, 1965). Table 14 summarizes the calculation and results.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PVT (2 mm, Eu)</th>
<th>Error (%)</th>
<th>PVT (5.9 mm)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total ADUs</td>
<td>1.04 x 10^6</td>
<td>2.0</td>
<td>1.13 x 10^6</td>
<td>5.15</td>
</tr>
<tr>
<td>Gain (photon/ADU)</td>
<td>0.664</td>
<td>-</td>
<td>0.664</td>
<td>-</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>0.71</td>
<td>1.4</td>
<td>0.70</td>
<td>1.4</td>
</tr>
<tr>
<td>CTE</td>
<td>0.983</td>
<td>1.0</td>
<td>0.983</td>
<td>1.0</td>
</tr>
<tr>
<td>Lens transmission</td>
<td>0.85</td>
<td>1.2</td>
<td>0.85</td>
<td>1.2</td>
</tr>
<tr>
<td>Effective f-stop</td>
<td>0.18</td>
<td>5.6</td>
<td>0.18</td>
<td>5.6</td>
</tr>
<tr>
<td>Mirror transmission</td>
<td>0.92</td>
<td>1.1</td>
<td>0.91</td>
<td>1.2</td>
</tr>
<tr>
<td>MCNP solid angle</td>
<td>1.44 x 10^-3</td>
<td>.21</td>
<td>1.44 x 10^-3</td>
<td>0.21</td>
</tr>
<tr>
<td>Total photons emitted</td>
<td>4.9 x 10^9</td>
<td>6.4</td>
<td>5.4 x 10^9</td>
<td>7.9</td>
</tr>
<tr>
<td>Energy deposition (MeV/n)</td>
<td>2.736 x 10^-05</td>
<td>.42</td>
<td>7.891 x 10^-05</td>
<td>0.42</td>
</tr>
<tr>
<td>Total energy deposited (MeV)</td>
<td>1.6 x 10^6</td>
<td>0.42</td>
<td>4.5 x 10^6</td>
<td>0.42</td>
</tr>
<tr>
<td>Light Yield (Photons/MeV)</td>
<td>3,100</td>
<td>6.4</td>
<td>1,200</td>
<td>8.0</td>
</tr>
</tbody>
</table>
The results show the PVT (2 mm, Eu) yields 2.6 ± 0.3 times more light than the PVT (5.9 mm). This is once again in agreement with the previous methods of comparing their light yields.

The PVT (5.9 mm) light yield value of 1,200 photons/MeV seems small when compared to its quoted value of 10,000 photons/MeV. The quoted value, however, is for electron energy deposition, which yields much more light than recoil proton energy deposition. In 1968, D. L. Smith compared the light yields of protons to electrons in a standard plastic scintillator, NE 102. A function was fitted to his reported values, as seen in Figure 30, in order to determine the ratio of light yield from 1.225 MeV protons, the average energy of a recoil proton from 2.45 MeV neutrons, to 1.225 MeV electrons.

![Figure 30: Ratio of proton to electron light yield in a plastic scintillator (NE 102)](image)

\[ y = -0.0025x^2 + 0.0688x + 0.1119 \]

\[ R^2 = 0.9983 \]
The light yield ratio of 1.225 MeV protons to electrons is approximately 0.19. Therefore, the anticipated light yield for the PVT (5.9 mm) for 2.45 neutrons should have been near 2,300 photons/MeV, which is nearly twice the found value of 1,200 photons/MeV. As seen in Table 14, there are several factors that determine the light yield of a scintillator with a CCD camera, but only two of them could lead to such a large error. Either the initial total signal of ADUs was too low, meaning the camera is not working properly or is not well suited for radiometry, or the energy deposition value was too high. Further experiments would be needed to isolate the error in this technique for determining the light yield of a scintillator. This technique shows promise, however, because the ratio of the calculated light yields was in agreement with the two other data analysis techniques.
Chapter 8: Conclusions and Future Work

This work provided a comparative analysis of scintillators for the final design and manufacturing of $^6$Li-loaded PVT scintillators for thermal and fast neutron imaging. Thermal neutron imaging of the $^6$Li scintillators demonstrated the degradation of resolution with thicker scintillators. A 1.1 mm increase in thickness decreased the spatial resolution by 11%, while increasing the $^6$Li-loading from 1.3% to 1.9% only yielded 4.5% more light/mm. GLO showed excellent promise as a thermal neutron imager because of its superior spatial resolution, 35 µm, and light yield when compared $^6$Li-Loaded PVT.

For fast neutrons at the OSURR, the $^6$Li-loaded scintillators produced 29% more light than standard PVT, confirming that $^6$Li enhances light yield for at least fast neutrons. However, the PVT (3.3 mm, 1.9%) produced the same amount of light as the PVT (2.2 mm, 1.3%), demonstrating the threshold of $^6$Li-loading must be below 1.9% for enhanced light yields for fast neutrons. For 2.45 MeV neutrons, PVT with the Eu fluor enhanced the light yield over standard PVT by $2.7 \pm 0.2$ times, which was within the estimated increase in light yield. An attempt was made to characterize the light yield of the scintillators in terms of photons/MeV. The technique for determining the magnitude of the light yield of a scintillator was inconclusive, but it showed merit because the ratio
of light yields were consistent with the Eu fluor producing 2.6 times more photons/MeV than the standard PVT.

In order to confirm the extent of increased light yield from $^6$Li-loading, more experimental time would be needed with fast neutron sources of varying energies. It is anticipated that there is an energy threshold where the $^6$Li-loading would cause a decrease in light yield. Based off this research, the recommendation to LLNL is to create scintillators of the exact same size and thickness in order to isolate the effect $^6$Li-loading and the Eu fluor have on light yield. The suggested size and shape of the scintillators to be tested is cylindrical with a 3 mm thickness and a 25.4 mm diameter. Four scintillators of this size were requested: standard PVT, which has a known light yield, $^6$Li-loaded (1.5%) PVT, PVT with a Eu fluor, and $^6$Li-loaded (1.5%) PVT with Eu fluor. This size makes multiple scattering events negligible, making it easier to determine energy deposition and detection efficiency. The 3 mm thickness is anticipated to provide an adequate signal to noise ratio for light yield comparisons and fast neutron imaging.
References


127 x 178 mm, 4-6 λ Mirror. (2014) Retrieved 1 26, 2016, from Edmund Optics: http://www.edmundoptics.com/optics/optical-mirrors/flat-mirrors/4-6-wave-first-surface-mirrors/41320/
Appendix A: MCNP6 Code: Probability of a Light Photon Reaching the Lens

PVT Simulation  
c  Cell Cards  
c Cell number, material number, density g/cm3, surface card geometry  
200 0 -20 imp:p=1 $lens  
400 7 -.001205 20 -50 imp:p=1 $ air inside  
999 0 50 imp:p=0 $ void outside  

c  Surface Cards  
c Cylinders  
20 RCC 0 11.56 0 0 1 0 .875 $lens  
c World  
50 so 20 $ problem boundary  

c  Data card  
mode p $ Neutrons D-D source 2.45MeV  
cut:p j .000001  
sdef par=2 erg=.000002 POS=0 0 0 AXS=0 1 0 EXT=d1 RAD=d2 $ PVT source  
SI1 0 .2  
SI2 0 1.255  

c  Material Definitions  
m7 6000.12p -.000124 $Air  
7014.12p -.755268  
8016.12p -.231781  
18000.12p -.012827  
c Detectors  
f1:p 20.3 $ Frontside of lens
Appendix B: MCNP6 Code: Sample Energy Deposition Code

PVT Simulation
c Cell Cards
c Cell number, material number, density g/cm3, surface card geometry
100 1 -1.032 -10 imp:n=1 $ PVT
200 8 -2.6989 -20 imp:n=1 $ Aluminum box
400 9 -.001205 10 20 -900 imp:n=1 $ air inside
999 0 900 imp:n=0 $ void outside

c Surface Cards
c Cylinders
10 RCC 0 0 0.05 0 0.22 1.255 $ PVT 25.1 mm diameter, h=2 mm
20 Box 7.62 7.62 -.001 -15.24 0 0 0 -15.24 0 0 0 .05 $box corner, x,y,z

c World
900 so 20 $ problem boundary

c Data card
c mode n $ Neutrons
cctme 5 $ limit run time
sdef pos=0 0 -.051 axs=0 0 1 ext=0 rad=d1 par=1 erg=1 vec=0 0 1 dir=1 $ beam source
SI1 0 1.5
SP1 0 1.5

c Material Definition
m1 1001 -0.0853 $PVT no Lithium
6000 -0.9119 $

c Detectors
f6:n 100 $ Energy Deposition
Appendix C: MATLAB Code: MTF Script

% Camera Data
HorPixel = 1940; % pixels for known length (approximately)
Pixelsize = .00454; % Pixel width in mm
FrameWidth = 39.4; % mm of known length
PMAG = HorPixel * Pixelsize / FrameWidth; % Primary Magnification
Sensor_lp = 1 / (2 * Pixelsize); % Sensor Lp/mm
lp_per_mm = Sensor_lp * PMAG; % cut-off frequency Nyquist cut off this is in lp/mm
pixels_per_mm = 2 * lp_per_mm; % how many pixels per mm
effective_pixel_size = 1000 / (2 * lp_per_mm); % um/pixel in the actual photo

disp(['The effective pixel size of the image is ', num2str(effective_pixel_size), ' um'])
disp(['The cut-off frequency is ', num2str(lp_per_mm), ' lines pairs per mm'])

calculateMTFr('GLOEdge63.tif', pixels_per_mm, 'y')
calculateMTFr('2mmEdgeMTF.tif', pixels_per_mm, 'g')
calculateMTFr('3mmE.tif', pixels_per_mm, 'r')

% calculateMTFr Fuction
function calculateMTFr(image, pixels_per_mm, color)
% subplot control
x = 1;
y = 3;

I = imread(image); % Matrix image from MTF_wrapper
[I_row, I_col] = size(I); % dimensions of image
AvgArray = sum(I) / I_row; % Average columns to create a single ESF
I = im2double(AvgArray); % Set singles ESF

ESF = I; % Edge Spread Function
ESF = ESF / max(ESF); % Normalize ESF

figure(1)
subplot(x, y, 1), plot(ESF, strcat(':', color), 'LineWidth', 2), hold on
ESFs = smooth(ESF, 6); % Smooth ESF
subplot(x, y, 1), plot(ESFs, color, 'LineWidth', 2), hold on

%% Line spread function (approximate derivative of ESF)
LSF = -diff(ESF);
subplot(x,y,2), plot(LSF, strcat(':',color), 'LineWidth',2), hold on
LSFs = -diff(ESFs);
subplot(x,y,2), plot(LSFs, color, 'LineWidth',2), hold on

%% Convert the spatial domain to frequency domain
Fs = pixels_per_mm;               % Sampling frequency (pixels per mm)
D = 1/Fs;                        % mm in picture each pixel covers
L = I_col;                       % number of pixel width of photo
NFFT = 2^nextpow2(L);            % Next power of 2 from length of L improves fft
f = (Fs)*linspace(0,1,NFFT/2+1); %linspace is a vector from a to b with c divisions, serves as x axis
% f creates an array of even divisions of pixel_per_mm value based on NFFT
%% Modulation transfer function
MTF = fft(LSF,NFFT);   %next power of 2 divisions of values for fft
MTFs = fft(LSFs,NFFT);
% Normalized plot of first NFFT/2 +1 entries of the MTF
subplot(x,y,3), plot(f,abs(MTF(1:NFFT/2+1)/max(MTF)) , strcat(':',color), 'LineWidth',2), hold on
axis([0 4 0 1])
subplot(x,y,3), plot(f,abs(MTFs(1:NFFT/2+1)/max(MTFs)) , color, 'LineWidth',2), hold on
axis([0 4 0 1])

%% Define plotting region Final MTF plot
figure(2)
if image(1:3) == 'ide'
    MTFs = MTF;
end
lw = 2;
plot(f,abs(MTFs(1:NFFT/2+1)/max(MTFs)), color, 'LineWidth',lw), hold on
end

plot(0:.01:20,.1,'k')
axis([0 20 0 1])%x and y axis dimensions
set(gca, 'XMinorGrid','on')
fs = 16; %font size of x and y labels
xlabel('Spatial frequency (lp/mm)', 'FontSize',fs)
ylabel('Modulation Transfer Factor', 'FontSize',fs)
title('Glass Target Modulation Transfer Function', 'FontSize',fs)
legend({'96% Pixel Saturation', '37% Pixel Saturation', '9% Pixel Saturation'}, 'FontSize',12)
% legend({'Paper Target','GLO','PVT(2.2mm,1.3%)','PVT(3.3mm,1.9%)'}, 'FontSize',12)
Appendix D: Photos of Tested Scintillators

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Dimensions (mm)</th>
<th>Picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVT (5.9mm)</td>
<td>75 x 75 x 5.9</td>
<td><img src="image1.png" alt="Picture" /></td>
</tr>
<tr>
<td>PVT (3.3 mm, 1.9%)</td>
<td>75 x 75 x 3.3</td>
<td><img src="image2.png" alt="Picture" /></td>
</tr>
<tr>
<td>PVT (2.2 mm, 1.3%)</td>
<td>75 x 75 x 2.2</td>
<td><img src="image3.png" alt="Picture" /></td>
</tr>
<tr>
<td>PVT (2 mm, Eu)</td>
<td>D = 25.1</td>
<td><img src="image4.png" alt="Picture" /></td>
</tr>
<tr>
<td></td>
<td>H = 2</td>
<td></td>
</tr>
<tr>
<td>PVT (1 mm, Eu)</td>
<td>D = 25.1</td>
<td><img src="image5.png" alt="Picture" /></td>
</tr>
<tr>
<td></td>
<td>H = 1</td>
<td></td>
</tr>
<tr>
<td>ZnS (1 mm)</td>
<td>D = 25.1</td>
<td><img src="image6.png" alt="Picture" /></td>
</tr>
<tr>
<td></td>
<td>H = 1</td>
<td></td>
</tr>
<tr>
<td>GLO (0.15 mm)</td>
<td>20 x 20 x 0.150</td>
<td><img src="image7.png" alt="Picture" /></td>
</tr>
</tbody>
</table>